Dissertationes Forestales 251

Innovative methods for measuring and improving the bearing capacity of forest roads

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Academic dissertation

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ABSTRACT

The aim of this thesis was to investigate the use of portable bearing capacity measurement devices and alternative fly ash structures to improve forest road quality and rehabilitation practices. So far, few tools have proved suitable for practical evaluation of forest road trafficability. Bearing capacity is the main component of trafficability and bearing capacity measurements are rarely conducted on forest roads. Replacing subjective criteria with objective measurement methods is the first step towards avoiding rutting damages as well as improving rehabilitation decisions.

Three bearing capacity measuring devices were tested for predicting forest road rutting in the context of bearing capacity improvements with fly ash structures. Modulus of elasticity (E-modulus) was used as the measurement unit. E-modulus was used to quantify road stiffness as measured by two portable measurement devices and one trailer-mounted device. A light falling weight deflectometer (LFWD) and a dynamic cone penetrometer (DCP) were used to challenge the conventional falling weight deflectometer (FWD). Test sections were located on forest roads with both mineral and peat subgrades. The comparison showed logical correlations between the measured E-modulus values, and reliable regression models are presented for the differences between measuring devices. In most cases DCP and LFWD can be utilized on forest roads instead of the expensive FWD. The measurement results for the portable devices and the FWD were compared to rutting, as represented by the increases in rut depth per passing truck (mm/pass) measured by mobile laser scanning (MLS). The devices were used to quantify the relationships between the E-modulus and rutting. Rutting threshold values were then based on these relations. A rough rutting susceptibility table was outlined to aid forestry professionals to estimate the rutting damage risk per timber truck on forest roads during periods of thaw-weakening.

Growing bioenergy production and consumption has resulted in an increase in the amount of fly ash produced by the forestry sector. At the same time the cost for ash deposition at land-fills has increased considerably. Utilizing fly ash in forest roads is therefore seen as a potentially cost-efficient alternative for improving bearing capacity. The fly ash part of the study investigated therefore road rehabilitation work from both technical and economical perspectives. Four different rehabilitation methods were tested using wood- and peat-based fly ash. The four rehabilitation methods involved two structures mixed with aggregate and two structures with uniform fly ash. The resulting bearing capacity of the rehabilitated road sections was improved compared to the reference sections, especially for the mixed structures. The improvements were verified by statistical comparisons. The study also defined the various work phases of rehabilitation and estimated construction costs based on phase-specific machine productivities. Cost calculation equations were established for earthwork and the transportation of construction materials. The lowest construction costs were calculated for a 250-mm thick uniform layer of fly ash structure, however, a 500-mm thick uniform layer of fly ash provided the lowest total costs when taking into consideration the alternative cost for landfill deposition.

Keywords: LFWD, DCP, FWD, rehabilitation, reconstruction, fly ash

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Bangkok, March 2018

Tomi Kaakkurivaara

LIST OF ORIGINAL ARTICLES

This dissertation is based on the following four (I–IV) articles, which are referred to by their Roman numerals in the text throughout this summary. All articles are reprints of previously published articles reprinted with the permission of the publisher.

I Kaakkurivaara T., Vuorimies N., Kolisoja P., Uusitalo J. (2015). Applicability of portable tools in assessing the bearing capacity of forest roads. Silva Fennica 49(2) article 1239.
http://dx.doi.org/10.14214/sf.1239

II Vuorimies N., Kolisoja P., Kaakkurivaara T., Uusitalo J. (2015). Estimation of risk for rutting on forest roads during thawing period of seasonal frost. Transportation Research Record: Journal of the Transportation Research Board 2474: 143–148.
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III Kaakkurivaara T., Kolisoja P., Uusitalo J., Vuorimies N. (2016). Fly ash in forest road rehabilitation. Croatian Journal of Forest Engineering 37(1): 119–130.

IV Kaakkurivaara T., Korpunen H. (2017). Increased fly ash utilization – value addition through forest road reconstruction. Canadian Journal of Civil Engineering 44(3): 223–231.
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The author's contribution

Tomi Kaakkurivaara is fully responsible for the summary part of the doctoral thesis "*Innovative methods for measuring and improving the bearing capacity of forest roads*".

In study I, Tomi Kaakkurivaara was mainly responsible planning of the study and the collecting bearing capacity data, executing statistical analyses and interpretations of the results. He was also the main writer and reviser of the manuscript.

In study II, Tomi Kaakkurivaara and Nuutti Vuorimies were responsible for planning of the study and collecting measurement data. The manuscript was mainly written by Nuutti Vuorimies with Tomi Kaakkurivaara.

In study III, Tomi Kaakkurivaara was mainly responsible for planning of the study, inventing the test structures, executing statistical analyses, and interpreting of the results. He was also the main writer and reviser of the manuscript.

In study IV, Tomi Kaakkurivaara was mainly responsible for planning of the study, defining work phases, collecting the cost factors data from machinery manufacturers, applying the productivities from previous studies our collecting own data, building the total cost models, executing cost calculations, analyzing the data and interpretations of the results. He was the main writer and reviser of the manuscript.

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LIST OF ABBREVIATIONS

a	Radius of the loading plate
AC_{dep}	Annual depreciation cost, €
AC_{fuel}	Annual fuel cost, €
$AC_{fuel\ tr}$	Annual fuel costs of tip truck and trailer, €
AC_{Ins}	Annual insurance cost, €
AC_{int}	Annual interest cost, €
AC_{lab}	Annual labour cost per person, €
$AC_{lab\ tot}$	Annual labour costs for personnel, €
$AC_{mac\ tot}$	Total annual machinery costs, €
AC_{overh}	Annual overhead costs, €
AC_{rep}	Annual repair and maintenance cost, €
A_{rs}	Annual risk and surplus target, %
AC_{tyre}	Annual tyre cost, €
AC_{tyre}	Annual tyre cost of tip truck and trailer, €
AC_{tot}	Total annual cost, €/year
AC_{tr}	Annual traveling and meal compensations, €
AC_{transp}	Annual transfer cost, €
AD	Annual driving distance of the tip truck and trailer, km
CBR	California Bearing Ratio, %
$C_{tr\ km}$	Cost of tip truck and trailer per kilometre, €/km
$C_{tr\ mass}$	Cost for cargo tonne of tip truck and trailer, €/tonne
d	Deflection under the LFWD loading plate
D_L	Driving distance per year, fully loaded, km
D_E	Driving distance per year, empty load, km
DPI	DCP Penetration Index, mm/blow
D_{sid}	Distance driven with a single load, km
E	soil's elastic modulus, MPa
$FCN_{tr\ L}$	Fuel consumption of tip truck, fully loaded, litres/100 km
$FCN_{tr\ E}$	Fuel consumption of tip truck, empty load, litres/100 km
HC_{tot}	Total operational hour cost, €/h
Int	Interest rate, %
IWC	Indirect wage cost, %
M_{tr}	Mass of a single cargo load, tonne
n_{lab}	Number of workers
$N_{tr\ tyre}$	Number of tyres of the tip truck, pcs
$N_{tl\ tyre}$	Number of tyres of the trailer, pcs
OHC	Overhead cost percentage, %
p	Vertical pressure on the loading plate
PF_{tr}	Price of fuel, €/litre
PP	Purchase price, €
$PR_{rm\ tyre}$	Price of a remoulding a tyre for truck or trailer, €
$PR_{tl\ tyre}$	Price of a new tyre for a trailer, €
$PR_{tr\ tyre}$	Price of a new tyre for a tip truck, €
SL	Service life, years
SL_{tyre}	Service life of a tyre, km
SV	Salvage value, €
TRM	Times that one tyre is remoulded per service life
WC	Wage cost, €/hour
WH	Working hours, hours/year

1 INTRODUCTION

1.1 Background and definitions of forest roads

The development of industrial wood utilization in Finland has changed timber transportation over time. Historically, timber transportation for the energy demand of households, towns and small-scale sawmills was accomplished using waterways, roads and later railways. The development of the forest industry in the1870s brought with it a growing demand for larger-scale timber transportation systems (Tasanen 2004).

Long-distance deliveries of timber by water transport was convenient in Finland via rivers and lake routes, with the primary transportation to being handled by horses. The first experiments with truck transport were carried out in the 1920s. In those days the undeveloped road networks and transportation equipment were the greatest obstacles for more extensive utilization. No information exists of when and where the first forest road was built for timber trucks in Finland. The first documentation of forest road transportation concerns the construction of a machine by W. Gutzeit & Co. in 1924 after the company failed to transport large volumes of timber during the previous winter due to poor weather conditions. The forest road led to a local village road, which connected via public roads to a railway station. Another historical event was the construction of a seven-kilometre forest road by the Forssa Company in 1928. It is mentioned as the first of its kind in Finland, and was planned and constructed for wood procurement. Forest road construction in these early days was normally conducted by other parties than forestry companies. These often aimed to ensure sufficient supply of firewood for their manufacturing plants. Timber haulage by trucks was initially concentrated on seasonal winter roads. Trucks became more common in the 1930s, particularly for timber transportation. The number of trucks in timber transportation increased, but remained a minor means of transport compared to the total transport volume. The possibility for railway and water transport increased when the combination of trucks and seasonal winter roads became a substitute for costly and labour-intensive timber rafting in streams and small rivers. The forest industry development came to a temporary halt during the 1940s due to the Second World War. Forest road construction then began on a larger scale during the 1950s, when the demand for timber grew rapidly. (Pakkanen and Leikola 2011)

The low density of forest road networks prevented forest resource utilization in many areas for a long period. During the 1950s approximately one fifth of Finnish forests were outside the zone of economical utilization. Harvesting and transportation costs in this zone were too high for profitable harvesting operations and the lack of knowledge and investment capital were obstacles for further forest road construction. The decision-making criteria for road building projects, however, were similar to today. The decision included economic calculations for decreased transportation costs and reaching as many potential logging areas from a single road as possible. Road construction was initially performed manually. Bulldozers were first introduced during the 1950s with backhoe tractors and excavators following later on. (Pakkanen and Leikola 2011)

The development of working methods and machinery influenced the construction methods for forest roads and their structure. The current condition of forest roads are partly both on the initial structures and their maintenance history. The most common construction methods used in the mid-1970s were a combination of bulldozer and backhoe tractor for preparing the sub-grade, after which the road was surfaced with a gravel layer delivered by gravel truck. Excavators were favoured over backhoe tractors in areas with low soil bearing capacity, numerous stumps or stones (Jukkola and Melkko 1975). Hydraulic excavators are now the most common construction method because of their flexibility for carrying out all the work phases prior to gravelling (Gerasimov et al. 2013). Excavators also have other advantages. They have a variety of attachments for various purposes, e.g. loading or excavating materials, breaking rock, shaping road alignments, levelling materials or even compacting embankment layers. In contrast to bulldozers, excavators have the ability to excavate and place material below or above the work platform (South African forest… 2008).

The most active period of forest road construction in Finland was during 1960–1990. Currently some hundreds of kilometres are still constructed annually, while previous levels exceeded thousands of kilometres (Metla 2014). The increasing coverage of forest road networks drove the gradual replacement of water transport with truck transport, enabled year-round harvesting instead of seasonal winter harvesting. The development of public roads also allowed a general increase in the gross vehicle weight and truck length (Fig. 1). Consequently, demands for forest roads have followed for higher bearing capacities and geometry in order to promote the competitiveness of Finnish forest sector.

Forest roads are part of the low-volume road (LVR) network. The ‘low-volume road’ definition also covers public roads with average daily traffic of less than 400 vehicles. Other features include low design speed and corresponding geometry. Many LVRs around the world consist of a single lane paved with gravel or even in-situ surfacing (Coghlan 1999; AASTHO 2001). Forest roads differ from public LRVs in a number of ways such as private ownership and less demanding design specifications, for example with respect to bearing capacity etc.

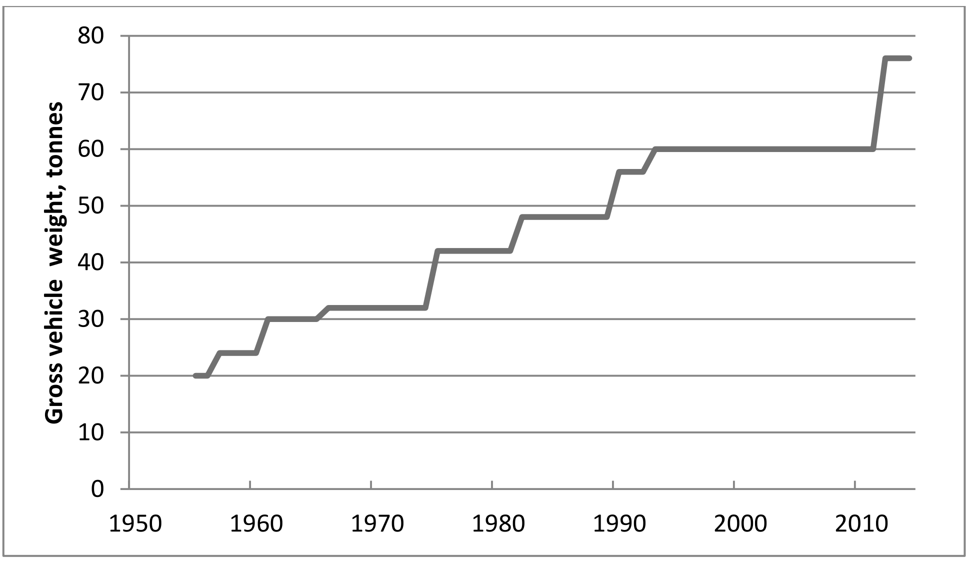

Figure 1. Development of maximum allowed gross vehicle weight in Finland (Pakkanen and Leikola 2011).

The forest road network is generally divided in three different road classes. These classes are categorized by different demands such as carrying capacity per day or year, driving speed, seasonal availability and expected life span. Road widths vary between countries depending on haulage vehicle constructions and traffic intensity. With respect to seasonal availability, primary roads are generally built for year-round operations to collect the haulage from lower-level forest roads. Secondary roads should be able to withstand timber haulages even during periods of lower bearing capacity such as the autumn. Spur roads constitute the bulk of the forest road network and provide access to logging units during the corresponding scheduled harvesting season, for example during the frozen or dry season for weaker sites (Pulkki 2003; Uusitalo 2010; New Zealand forest… 2011)

Forest roads are generally constructed partly from materials available at the road construction site, and partly of materials transported from elsewhere. Textbooks and road construction instructions (e.g. Skogsbilvägar – service, underhåll… 1991; Metsätieohjeisto 2001; Pulkki 2003; Uusitalo 2010) divide forest road structures into two major structural elements: subgrade and pavement (Fig. 2). The subgrade is composed of in-situ materials and forms the underlying structural layer of the road. It includes embankment fill material from ditches or cutting materials from slopes. Pavement is built on top of the subgrade and can be subdivided into a surface layer, a base-course layer and a sub-base layer. The sub-base layer is used to separate the upper layers of the pavement from the subgrade, and is usually composed of coarse-grained sand or gravel, which cuts the capillary rise of water from the subgrade into the pavement. The sub-base layer can be substituted by geotextile in challenging sections. It is not a necessary layer if the subgrade is not frost-susceptible soil. The base-coarse layer is generally made of coarse gravel material or crushed rock. These materials, which give the road its structure and most of its load bearing capacity, are generally called construction aggregate or simply aggregate. The surface layer is composed of finer sieved or crushed materials.

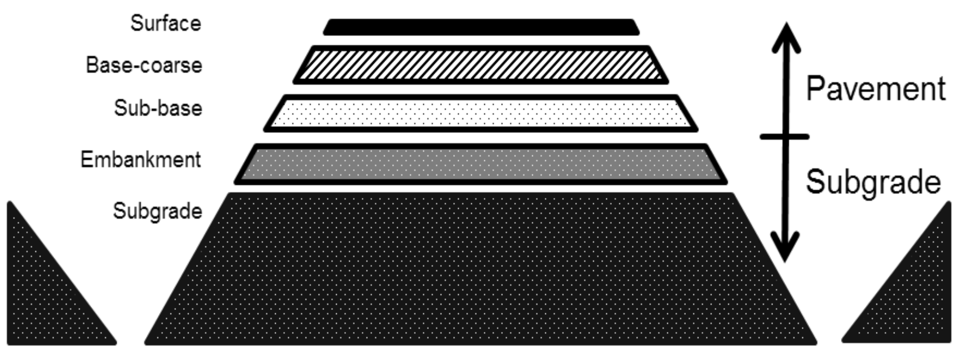

Figure 2. Typical forest road elements and construction layers.

1.2 The current situation, problems and future demands of forest roads

Finland has approximately 135 000 kilometres of forest roads, of which 3000–4000 are rehabilitated annually (Metla 2014). These roads are the backbone of forestry, providing access to logging sites and enabling the transportation of timber from forests to mills, railways or floating terminals. They also provide access for forest machines, silvicultural operations and forest mensuration, as well as for forest recreation. These latter aspects are also significant, but will not be dealt with further in this thesis.

Finnish forestry has now a sustained demand to increase year-round timber transportation. Previously, the forest industry has stored raw materials on the mill grounds to satisfy its needs during the spring thaw. Forestry companies currently try to minimize the intermediate storage of roundwood, where deterioration during long storage times can degrade the quality of end products. Another important factor in this context is to reduce the capital bound in inventories. Timber trucking contractors have earlier expressed concern about LVR conditions (Malinen et al. 2014), where winter maintenance has been the greatest cause of concern. However, the dimensions and conditions of LVRs, seasonal lack of bearing capacity and the number of thaw-damaged roads, have also been mentioned.

The need for uninterrupted year-round wood procurement even during the thawing season is a challenge for the network of public LVRs, private local roads and forest roads, in particular. The main bulk of the Finnish forest road network was constructed more than a quarter of a century ago. Many road sections are therefore nearing the end of their technical life cycle and require rehabilitation in the near future. The bearing capacity of the forest road network also requires upgrading as truck gross vehicle weights increase. Climate change is assumed to have a negative impact on the bearing capacity of the road network. Autumn rainfall, in particular, appears to be a growing concern, and the winter frost has become shorter and more intermittent. Furthermore, some roads did not meet construction guidelines, even initially. Many lack the above-mentioned standard four-layer structure, particularly for spur roads. These roads have only two major layers: a subgrade with embankment fill, sources primarily from ditches, and a thin constructed layer of aggregate or gravel. In many cases, these roads represent bottlenecks in the transportation network.

These forest roads often have very low traffic volumes. The key point is therefore to minimize costs for maintaining their trafficability. The aim is therefore to keep trafficability at an adequate quality level with minimum investment. Despite this, road construction costs should reflect the frequency and intensity of use. As a consequence of demands to minimize costs, forest roads are typically made of low-quality materials with the constructed layers often being mixed with each other or with the subgrade. Freeze-thaw cycles and seasonal changes are important factors in northern regions, as these affect a road’s driving condition and bearing capacity. In many cases in Finland major rehabilitation operations should be executed before timber haulage, where forest roads have reached the end of their technical service life and are not capable of carrying heavy vehicles. Present day requirements have developed considerably from when these roads were originally constructed, as have the forest industry demands for fresh wood, also in the springtime. The necessary timber volume for milling during the thawing period cannot be stored at the roadside or in terminals in advance so year-round availability of forest roads with heavier and longer timber trucks is crucial. Increased knowledge of forest road conditions and rehabilitation needs are therefore vital to ensure effective wood procurement.

1.3 Measurement methodology for bearing capacity

Stiffness or modulus of elasticity is commonly used terms for quantifying bearing capacity and trafficability of forest roads. Measured stiffness values can be used for two different purposes. Firstly, for assessing the necessity of repair work on a road. Secondly, for assessing daily trafficability during the spring thaw, when most difficulties concerning bearing capacity occur. In light of the above, it would be advantageous for transport planning staff to have access to simple methods for evaluating the bearing capacity and trafficability of forest roads.

Several measurement devices can be used to measure the bearing capacity of roads. These devices can be divided into four categories based on the loading method used: (1) vibration, (2) wave propagation, (3) static and slowly moving loads and (4) the impulse method (George 2003). The last mentioned method is currently the most common method in use. The static method, e.g. the plate-loading test, is theoretically sound, but it poorly mimics the load caused by moving traffic on LVRs. Most measuring devices express their measurement results in terms of elastic modulus (E-modulus). This well-established method is used in highway engineering for evaluating the bearing capacity of roads using a Falling Weight Deflectometer (FWD). The FWD is a commonly used device on the paved LVRs of Finland, but it has also been used on unpaved forest roads (Saarenketo and Aho 2005). FWD mimics the wheel load of a truck quite well, and it is trailer-mounted and towed by a van. The measurement procedure is sophisticated and computer-aided. The measurement results are then used to back-calculate the stiffness of a road's structural layers. Miller et al. (2011) found that during thaw-weakened periods FWD could also be applied for assessing the accessibility of forest roads. The disadvantage of this method is that the FWD measuring services are costly and must be ordered before the actual need for measurement appears. The immediate availability of the measurement service when weather patterns require its use may also prove an obstacle to increased application.

Inexpensive devices, which are lighter and easier to use than the traditional FWD, are currently available. These can fulfil the need to find easier-to-use and readily available measurement methods that enable rapid local evaluation of forest road bearing capacity. Two potentially suitable methods are the light falling weight deflectometer (LFWD) and the dynamic cone penetrometer (DCP) test. The definition for LFWD covers a wide variety of portable small-scale devices. The Finnish Loadman is one such a device, initially designed to assess the level of compaction and bearing capacity of unbound and bound pavements. The DCP has been a commonly used device for forest roads over decades, but the method deviates from that used in FWD and LFWD. The DCP device has a cone tip that penetrates into the soil and assesses the strength of the soil based on conversion parameters derived from empirical tests.

Correlations between portable measurement devices and more conventional methods have been studied, most often to obtain reliable measurements from portable tools or FWD. However, not many studies have been published on their usability and mutual conformity for forest road. No studies have been published in Finland concerning bearing capacity measurements on forest roads since Pulkki (1982), who compared usability between FWD, the plate loading test (Benkelman beam) and a light seismic method. The dissertation observed that the light seismic method was a promising device for bearing capacity assessment. The Benkelman beam has also been studied by O'Mahony et al. (2000) on a forest access road built on peat subgrade. The device was able to show that the thickness of the peat subgrade impacts the bearing capacity of flexible pavements. This observation was also the reason for separately studying forest roads built on mineral and peat subgrade in this thesis. The LFWD has shown promising results for reliably measuring seasonal stiffness variations on LVR (Kestler et al. 2007). The results were also comparable to an FWD-derived modulus. A few studies have been conducted on forest roads or gravel roads, which encouraged investigating the connection between measured bearing capacity results and road characteristics in this thesis. Significant correlations were detected between moisture content of soil samples, DCP penetration index and LFWD modulus, irrespective of the impact caused by soil type and moisture content of granular and fine-grained soils. (Siekmeier et al. 2009). Grain size distribution also had a significant influence on the DCP penetration index. Dai and Kremer (2005) have shown the relationship between the DCP modulus, moisture content and soil densities. DCP usefulness has been tested by Mohammadi et al. (2008) in laboratory circumstances, which showed how DCP values correlate with the bulk density of sandy soil.

Published usability studies of measurement devices have mainly targeted highways, which commonly have thick structural layers and are paved by hot mix asphalt. Strong correlations were detected between the DCP, FWD and moisture content when the subgrades of highway-quality roads were divided into fine- and coarse-grained subgrades, when the resilient modulus was determined by DCP in-situ or measured in a laboratory (George and Uddin 2000). George (2003) showed the correlation between the DCP and FWD in paved roads. LFWD (Loadman) and FWD were effective devices for determining properties of compacted unbound material and for indicating future performance of flexible pavement with respect to rutting, whereas the Glegg hammer (impulse method) and nuclear density meter (wave propagation method) were insufficient in these respects (Pidwerbesky 1997a). Siekmeyer et al. (2009) and Von Quintus et al. (2008) also introduced and verified the usability of portable measurement tools for the quality control of road structure construction. These studies were carried out on highways that followed established construction specifications. Forest roads are typically constructed with less strict adherence to design specifications. Based on the above-described situation, more knowledge is needed on the suitability of stiffness measurement devices for forest roads.

All forest road users, e.g. timber transportation, encounter significant problems during springtime. Reduced axle loads and weight limits prevent serious damages, such as deep ruts, which are costly to repair. The utilization of bearing capacity measurement devices have been studied for setting load restrictions on thaw-weakened roads. Steinert et al. (2005) studied the effectiveness of the portable falling weight deflectometer (PFWD) in assessing the bearing capacity of roads during frost thaw. They observed that using the PFWD was as suitable for assessment as the FWD, when the highest drop height, heaviest falling weight and largest base plate diameter was implemented in the PFWD. If the earlier bearing capacity history of the road is known, the PFWD allows a more optimal selection of periods for load restrictions due to the thawing period. The LFWD in this thesis does not include similar measurement options as the PFWD, which justifies investigation of the Loadman in particular. Embacher's (2006) study showed that the DCP values profile was an ingenious indicator of changing seasonal bearing capacity, as he investigated the possibilities of using DCP for monitoring the seasonal variation in stiffness. Moreover, a study by Paige-Green and Du Plessis (2009) proposed use of the DCP for rehabilitating roads in advance by presenting design curves for the DCP. Estimating how much loading an existing road can carry or which principle should be followed in repairing the road to achieve the desired stiffness is possible with the help of design curves. A deformation study was conducted by Brito (2011), who measured the rutting and bearing capacities of various road structures, but in this case the measured ruts were the result of thousands of heavy axles on the LVR. LVR studies typically subject the roads to thousands of passes with different axle loads and tyre types, which does not accurately simulate the loading of timber haulage on thaw-weakened forest roads. In contrast, timber transportation operations are carried out on forest roads with even weaker bearing capacity levels than public LVRs, as forest roads often lack proper road structures and only a few vehicle passes are conducted with maximum axle loads.

1.4 Fly ash for the rehabilitation of forest roads

Ash is a by-product of the burning process of coal or biomass-based materials. The end product of this process is either electricity or heat and electricity. Globally the main producers of coal ash are India and China, where annual production is approximately 100 million tonnes (Dwivedi and Jain 2014). Decreasing coal usage for energy means reduced coal production in the OECD countries and China (IEA 2017). Due to rising concern about carbon dioxide (CO_2) emissions, coal-based energy production may be changing permanently, despite its strong present position (Karl and Lippelt 2011) and biofuels represent potential substitute resources for power plants. Wood-based bioenergy is therefore becoming a more viable choice not only in Finland, but also in other forested countries. Increasing forest bioenergy utilization means increased quantities of wood-based ash. In Finland, approximately 600 000 tonnes of wood- and peat-based fly ash are produced annually, of which the forest industry produces a significant proportion (Emilsson 2006). The total ash production is approx. 1.5 million tonnes per year in Finland. At present there are 52 power plants around the country with an annual ash output of at least 1000 tonnes per plant. Fly ash is the main type used in ash production, while bed ash is used to a lesser degree. (Tuhkarakentamisen käsikirja 2012)

As a result of growing bioenergy production, the power plants of the forest industry and the heating plants of communities are confronted with the problem of how to utilize increasing quantities of ash. Finding possibilities for ash utilization is crucial because of environment policies where waste deposition charges are rising in Europe. In Finland, for example, waste taxes were raised to €70 per tonne in 2016 (Finlex 2015). Technically- and economically feasible methods for utilizing ash are therefore more relevant than earlier. Several potential and beneficial ways of using ash currently exist. These include: serving as a construction material in road building, reducing the need for natural stone resources (Edil and Benson 2007), as a filler in concrete (Wang et al. 2008) or as a fertilizer in forests to increase timber growth (Moilanen et al. 2005) or field crops in agricultural use (Patterson et al. 2004). In Finland, the quantities of ash utilization are divided roughly equally between landfills, earthwork and fertilizers or other use. One third of ash production still ends up in landfills, with significant costs for power plants (Ojala 2010). Financial savings from reduced dumping charges can be achieved through ash utilization in construction layers of forest roads. A higher ash-utilization rate could also increase employment of earthmoving and transportation entrepreneurs. The forest and energy industries no longer consider ash as disposable waste, but rather as a by-product of business, to be utilized in various ways. This thesis focuses on fly ash; a by-product from burning wood and peat sources in power plants.

The expansion of ash utilization is confronted by numerous obstacles. Ash has several specific characteristics which impact its potential application in civil engineering work. Ash is classified as fly ash or bottom ash based on particle size. Classification of fly ash based on its grain size is similar to silt. Consequently the fly ash structure is a non-resistant material with poor bearing capacity. The properties of fly ash originating from wood and peat varies depending on the burning process, the fuel mix used and combustion gas filtering technique (Korpijärvi et al. 2009). Generally speaking, the technical properties of ash are not as stable and constant as mineral soil. Nevertheless, given its calcium oxide content, fly ash structure can create a high and stable bearing capacity given sufficient compaction work and optimum water content (Tuhkarakentamisen käsikirja 2012). In addition to technical characteristics the content of environmentally harmful heavy metals needs to be considered when planning ash utilization.

Conventional forest road rehabilitation has commonly used a particular sieve size of gravel or aggregate, while ash has rarely been utilized so far. The flexible licensing policy allows the use of ash in the structural layers of public roads (Tuhkarakentamisen käsikirja 2012). Forest roads, however, do not belong to the same permission policy class. Ash utilization on forest roads requires a more detailed approval procedure. However, ash utilization in road structures is now receiving more attention. Related studies have primarily focused on coal ash due to the prevalence of coal utilization in energy production. The use of both bio ash (Lahtinen 2001) and coal ash (Edil and Benson 2007) have been studied on LVRs. Both studies observed ash to be well-suited for road construction. Proper ash utilization would also improve the bearing capacity of forest roads. Wood-based fly and bottom ash were utilized in forest roads by mixing materials directly to the existing road structure (Bohrn and Stampfer 2014). Improved bearing capacity was tested based on PFWD measurements, where data were collected during half-year observation period. Supancic and Obernberger (2012) carried out both a laboratory test and field study using wood fly ash and bottom ash. The LFWD measurements indicated a positive impact on bearing capacity during a four-week monitoring period. Vestin et al. (2012) studied wood fly ash mixed into the gravel of an existing road. The FWD measurements were carried out over a year-and-a-half monitoring period, which showed improvements in bearing capacity. For all three studies, the ash was mixed into existing road structures and short-term studies were conducted on bearing capacity. The old road structures were broken using a road grader and the ash functioned as a binding component for the new structure.

1.5 Economical comparison of fly ash structures

Currently no studies have been published concerning the utilization of fly ash in forest roads from an economic efficiency viewpoint. Kumar and Patil (2006) studied the profitability of fly ash utilization on public roads, and showed that fly ash construction could decrease the demand for conventional materials and their transportation. The study also indicated that using less conventional construction materials would reduce total costs. Ghajar et al. (2013) described the work phases of forest road construction which are not usable for fly ash rehabilitation. In North America, general cost and prices have been published widely for the various work phases of forest road construction (Kochenderfer et al. 1984; Balcom 1988; Cost estimating guide… 2011; Conrad et al. 2012). Cost information is confined to time and place, so results of these studies cannot be directly utilized in this thesis. A literature review did not reveal any available cost calculation models for fly ash construction on forest road systems. As the fly ash requires certain types of treatment and construction techniques, these aspects are further scrutinized in this thesis.

Minimizing the costs of new forest road network planning and construction has been the main focus of previous forest road cost studies (Akay 2003; Akay and Sessions 2005; Abdi et al. 2009; Ghajar et al. 2013). These studies did not compare different road materials; instead their focus was on the effects of forest road alignment on construction costs. A demand exists for cost calculation models that can be applied for estimating the economic performance of forest road construction, maintenance and repair, also including consideration of road material selection. The basic idea of such cost calculations is to include all factors essential to cost objects with precise identifications and determinations. In most cases cost factors are divided into variable and fixed costs. Raw material, fuel and tyre costs are counted as variable costs, while interest, capital and annual depreciation are fixed costs. Labour costs are normally counted as separate cost factor (Sessions and Sessions 1992). All cost factors must be allocated to their respective calculation objects to obtain total costs, which include all the determined cost factors summed together. Every relevant process and road material has to go through the economic evaluations with comparisons based on these calculations. This approach provides better options for finding causal connections which may otherwise remain hidden, e.g. when relying solely on statistical average values.

The previously-mentioned need to achieve even year-round supply of raw material to the forest industry requires a corresponding trafficability of forest roads. This becomes problematic when the bearing capacity of forest roads is at its lowest level during the spring thaw when the moisture content of the road structure is high (Salour and Erlingsson 2013). To enable year-round traffic, the forest road network must be built or rehabilitated to correspond with the seasonal quality requirements. Otherwise, without weight restrictions on forest roads during the periods of low bearing capacity, traffic during the thawing period will break down the road structure. Higher bearing capacity would also assist wood supply management and decrease the subsequent need for road repairs after rut formation. No technical obstacles exist for upgrading existing forest roads or building new roads for year-round use, but rising costs are a hindrance from the economic viewpoint. Such investments will not be undertaken as long as costs are high and not offset by benefits in harvesting, transportation and other forestry operations. For Finland, approximately 10% of the total forestry costs are allocated to forest road maintenance (Piiparinen 2003). Forest road construction and maintenance should be executed with minimal costs without jeopardizing the logistics of wood procurement. In this context, rehabilitation utilizing ash could be beneficial to both individual forest roads and to forest industry in the wider context. Accurate estimation of construction costs would enable objective decision-making for fly ash utilization on forest roads, which is challenging with the current knowledge level. In this thesis, a bottom-up approach to forest road construction and cost calculation modelling were used to provide the necessary information for more efficient and rational decision-making.

1.6 Thesis objectives

The main objective of the thesis was to evaluate the appropriateness of portable measurement devices for assessing bearing capacity and corresponding risk of rutting on forest roads together with the feasibility of exploiting fly ash in forest road structures. The thesis aims to answer the following research questions: How to measure bearing capacity in a reliable way? How to avoid rutting caused by timber haulage? Which is the technically and economically best way to utilize fly ash for road rehabilitation? These questions are limited to gravel forest roads. The thesis contains 4 studies. The objectives of studies I–IV and key aspects were as follows:

I The objective of the first study was to estimate the applicability of the LFWD and the DCP in assessing the bearing capacity of forest roads. The evaluation was based on a comparison of the measurement results for the portable measuring tools with the FWD. The study examines links between measured bearing capacity values and road characteristics. The accuracy of these measurement results should be adequate so that the devices can replace the FWD. An efficient and dependable method for estimating bearing capacity would enable more objective decision-making for maintenance and repair of forest roads than current approximate estimations given by visual observation.

II The objective of the second study was to measure how well the measurement of bearing capacity by LFWD, DCP and FWD assisted in determining the risk of rapid rutting on a forest road. The usability of the different measurement devices was tested with respect to evaluating the trafficability of a forest road for heavy vehicles during the period of frost-thawing. The focus was on the use of portable tool measurements due to their flexibility and ease of use.

III The objective of the third study was to investigate the potential use of fly ash from biofuel power plants for forest road rehabilitation. Four different fly ash test structures and a reference structure were built. Two test structures included only fly ash, while the other two contained fly ash mixed with aggregate. Bearing capacity developments were measured with the LFWD, the DCP and the FWD. The improvement in bearing capacity of the test structures and reference structure were compared. A special focus was on comparing the bearing capacity during the spring thaw, when bearing capacity is at its lowest.

IV The objective of the fourth study was to study the economic aspects of utilizing fly ash for the rehabilitation of forest roads. A cost calculation model was formed for fly ash rehabilitation of forest roads. The fly ash test structures from the third paper were used for the calculations. The study included a definition of the work phases, usable machines and their productivities. The idea was to compare the economic efficiency of the four test structure types with a regular method including the alternative cost of fly ash landfill deposition.

Together, these four studies contributed to providing innovative methods for forest road maintenance and rehabilitation. For this process, it was essential to first study the relationship between road characteristics and results of the measurement devices. Thereafter, it was important to utilize this knowledge to predict the rutting of a forest road during haulage. The final aspect concerns the search for cost-efficient and environmentally safe materials for forest road rehabilitation.

2 MATERIAL AND METHODS

2.1 Background

Bearing capacity studies are long-lasting by nature. The data collection period for this thesis was several years, which would be impossible without committed partners and long-term funding. All portable tool and moisture content measurements were made by the Finnish Forest Research Institute (Metla, nowadays the Natural Resources Institute Finland, Luke) in studies I–III. An outsourcing service was used for the FWD measurements in studies I–III and the mobile laser scanning (MLS) measurements in study II. The particle size distribution of the soil samples was determined by Metla. Based on these determinations, theoretical E-modulus values were estimated by the Tampere University of Technology. Weather station data were collected and analysed by Soilmetric Oy. Test road sections for studies I–II and III were located on roads owned by Metsähallitus and UPM Company, respectively. The DCP device used was a K-100 Int., manufactured by Kessler Soils Engineering Products, Inc. The LFWD was a Loadman developed by AL-Engineering Ltd of Finland.

2.2 Measurement devices

2.2.1 Studies I–III

The same DCP device was used for all the measurements in this thesis (Fig. 3). The measurement procedure was based on the impact force of a falling weight, which pushed a cone tip into the ground. The device includes the following parts: an 8-kg falling weight attached to a ca. 575-mm long rod, an anvil for dropping the weight, a steel rod with a 20-mm cone diameter, a 60-degree angle of the tip and a vertical scale about one metre in length to detect the penetration depth of the blows (ASTM 2005; Hossain and Apeagyei 2010). The vertical penetration (mm) after each drop or several drops can be measured and computed as the DCP Penetration Index (mm/blow), hereafter referred to as DPI. The DPI is basis value used to calculate the California Bearing Ratio (CBR), which is based on an empirical equation (Equation 1) (Webster et al. 1992). To compare DCP measurements to other device measurements, the CBR value was converted to an E-modulus by another empirical equation (Equation 2) (Powell et al. 1984). These above-mentioned equations are widely used by other professionals and researchers in their studies, which is why they can be considered well researched and tested in practise compared to other available alternatives. (Livneh et al. 1995; Siekmeier et al. 1999; Wu and Sargand 2007).

$$\log \mathrm{CBR} = 2.46 - 1.12 \log \mathrm{DPI} \quad (1)$$

$$\mathrm{E} = 17.6 * \mathrm{CBR}^{0.64} \quad (2)$$

The soil E-modulus values, based on the DCP measurements and derived from Equations 1 and 2, are hereafter denoted as E_{DCP} in this thesis. These non-theoretical equations enabled the comparison of results with results from other studied devices. The E-modulus cannot be directly measured using the DCP device.

Figure 3. Measuring devices DCP, LFWD and FWD.

The LFWD also has a falling weight, just as the DCP, but instead of penetration it measures the deflection (Fig. 3). The measurement operation is based on momentary deflection of the ground surface. The main features of the device include: a 132-mm diameter loading plate, a 10-kg falling weight, an 800-mm long tube for the dropping weight, an accelerometer and an LCD screen. Measurement results were stored in the memory files and were transferrable to a computer via a USB connection. For reliable measurement, each of the studies used the third drop at each measurement point for the calculations. This is important in forest road circumstances, because the influence of a loose surface layer needs to be minimized on unbound pavements (Gros 1993). The LFWD provides three measurement values: maximum deflection (mm), E-modulus (MPa) and compaction ratio, which is calculated and showed by the internal electronics of the device after each measurement. It translates acceleration into displacement and, based on the known load, calculates a modulus value using Equation 3 (Pidwerbesky 1997a).

$$E = 1.5 * \frac{p*a}{d} \qquad (3)$$

E_{LFWD} is used in this thesis to indicate the E-modulus yielded by the LFWD. Equation 3 is well known and commonly used all around the world. There is no straight connection between the ground reflection and E-modulus. It is an empirical equation, which has been robustly tested. Lastly, it is important to note that LFWD measurements represent only about 200 mm from the top of the road structure.

The FWD was chosen for this thesis as it represents an established and conventional measurement device (Fig. 3). The operating principle and E-modulus equation (3) used for calculating the FWD were equivalent to for the LFWD. Differences included a falling weight that causes a deflection as it is dropped from four different heights onto the loading plate. It has a much heavier impulse load than the LFWD. The highest drop (4^{th}) denotes a mass of 5000 kg, which simulates a moving wheel load quite well. Another difference compared to the LFWD was the number and location of the deflection observation points. The FWD has several seismometers placed at certain intervals from the loading plate to collect deflection observations. These deflection values generate deflection curves, which provide information concerning the capacities of the deeper structural layers to carry truck loads. The inner FWD sensors react more to surface behaviour and the outer sensors to the deeper layers and subgrade (Miller et al. 2011). In this thesis, the E-modulus of the entire structure measured with the FWD has been denoted as E_{FWD}. In addition to these measures, the base curvature index (BCI), surface curvature index (SCI) and intermediate depths have their own parameters, which describe the stiffness of a particular structure. Measured information was therefore available from the pavement layers and subgrade.

2.2.2 Study II

The rutting prediction study included loading a road using a gravel truck and gathering surface measurements using MLS technology (Fig. 4). The test road sections were scanned before and after the loading runs of the gravel truck. The laser scanning data provided a road surface elevation map. A comparison was made between the road crown of the road and the rut bottom and between the loading runs. Average rutting was divided by the number of gravel truck passes and the total rut depth. The loading vehicle was a four-axle gravel truck tractor with a total mass of approximately 34 tonnes. It passed over the test road sections eight to fourteen times. The study was carried out in May 2012 and 2013 during the spring thawing period. The repetition was discontinued before any risk of severe damages was actualized.

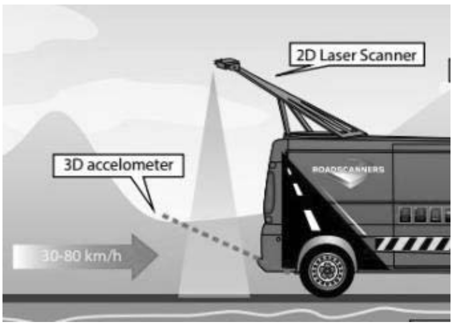

Figure 4. Mobile Laser Scanning technology provides information of road surface shape (Drawing by Roadscanner Oy).

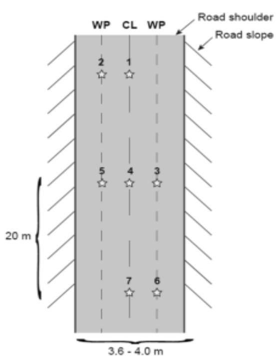

Figure 5. Measurement point layout along the test road section. Numbers 1–7 stand for the measurement points, WP denotes the wheel path and CL denotes the centre line.

2.3 Test roads and field data collection

2.3.1 Measurement point layout in studies I–III

Test road sections were comprised of similar measuring point layouts for each of the studies in this thesis (Fig. 5). Each included seven measurement points situated transversely and longitudinally on the forest road. Four out of seven points were located on the wheel path (WP) and three on the centre line (CL). Later the division into wheel path and centre line was also used in the statistical analyses and results tables of the studies. Another division was made between mineral and peat subgrades in studies I and II. This division was implemented by establishing paired test sections on the same forest road, close to each other. One test road section was 60 m long. The road sections and measurement points were marked by poles at the roadside, which ensured finding the right location during following years.

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2.3.2 Test section locations and data collection in studies I and II

The test road sections for bearing capacity measurements were located in Parkano and Ylöjärvi municipalities in Western Finland (Fig. 6). The measurements were carried out on 24 test road sections. In ten cases mineral and peat soil stretches on the same road, separated by no more than 1000 metres from each other, were paired together to make these sections. The remaining four test road sections were located by themselves on peat soil. The data from these test road sections were collected in 2009–2012. Five separate measurement rounds were conducted, one in summer and four in springs during the frost-thawing period. In other words measurements were conducted in May, as the thawing period does not always occur at the same time in spring. Data collection was scheduled to begin when the frost had already melted from the road structure. This means that the structure was still saturated by water, but frozen structures did not disrupt the DCP and FWD measurements.

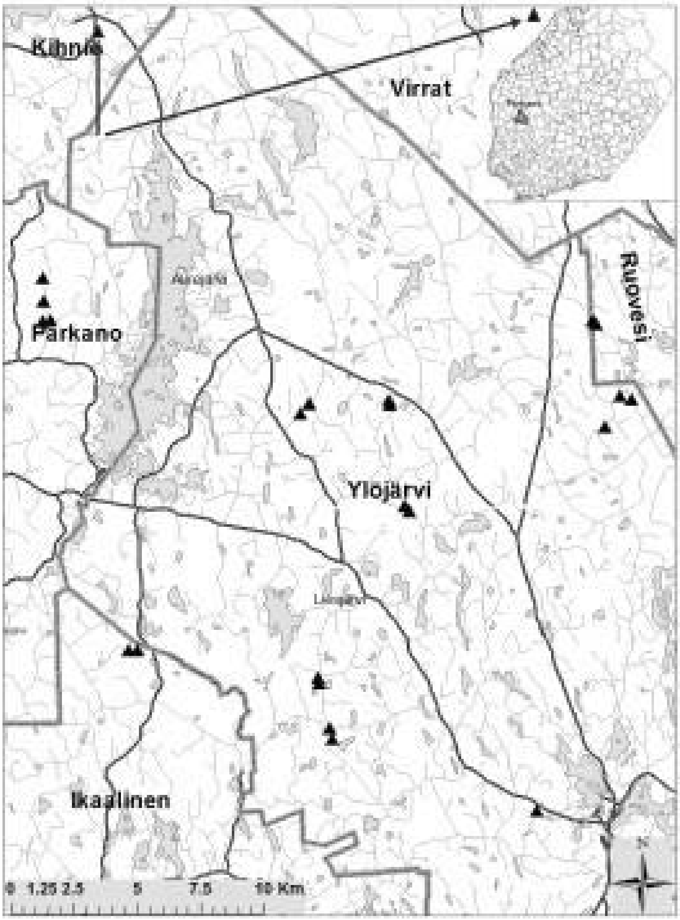


Figure 6. Test road sections marked on the map using triangle symbols. Two of the test road sections are located outside of the map area. The thinner grey lines denote low-volume roads and the black thicker line denote main roads.

2.3.3 Test section locations and data collection in study III

The test sections were established for fly ash structures on forest roads, which were located in the same area in Central Finland near the Jämsä municipality (Fig. 7). A total of ten test sections were established on two forest roads near each other, five on both forest roads. Four different fly ash structures and a reference structure for monitoring bearing capacity during the following years were constructed on both forest roads. The test sections and measurement points were clearly marked using poles at the roadside before rehabilitation in summer 2011. The measurements were carried out during summertime before and after rehabilitation in 2011 and 2012. Springtime was the main season of interest, and seasonal measurements were carried out during years 2012–2014. The mean values for E_{LFWD} and E_{DCP} were calculated from eight measurement points from the wheel path and six from the centre line. The mean values for E_{FWD} were based on two measurement points from the centre line and four measurement points from the wheel path. These measurements were part of the measurement round for each test structure.

2.4 Weather characteristics for 2010–2012

The climate in the study area is subarctic and winter is the longest season. The area is classified as Dfc (subarctic climate) in the Köppen-Geiger climate classification system (Kottek et al. 2006). Weather conditions were monitored during winters 2010–2011 and 2011–2012, to gain more specific information for this thesis. A weather station was established at test section 131a/b (Table 1, study I), which is marked by the triangle symbol on the far right (Fig. 1, study I). The total amount of sub-zero Celsius degrees were cumulatively calculated for both winters. Additionally, maximum frost depth was monitored from the centre line of the road. The first surveyed winter was cold. The cumulative sub-zero temperature was 31 530˚Ch and frost depth reached 157 cm, which according to statistics occurs ca. once every five years. Winter 2011–2012 on the other hand was very mild, the cumulative sub-zero temperature was only 12 900˚Ch and frost depth reached 86 cm. The thick frost layer was caused by the removal of snow, as the forest road was ploughed for a portion of the winter to clear it for timber haulage. Annual difficulties with springtime trafficability are therefore typical in the area during the frost thawing on the road structures.

Figure 7. The location of test road sections for fly ash structures near Jämsä. Ref. denotes reference structure, numbers 50 and 25 stand for uniform fly ash structures, and numbers 5+10 and 10+10 stand for mixed aggregate and fly ash structure.

2.5 Soil sample analyses of studies I and III

Soil samples were collected from every test road section to determine the grain size distribution curve using the wet sieving and pipette methods (Haywick, 2004). Particle size distributions of the road materials were investigated using sieve sizes of 0.63, 2, 6.3, and 2.0 mm. The burning method (ASTM, 1993) was used to determine the organic content from the <2-mm grain size. For study I, soil samples were taken from each road structure layer: the aggregate layer, embankment fill and subgrade, if separating a particular layer was possible. Subgrade soil samples could not be taken from the test section roads constructed on peat. For study III, samples were collected from the initial aggregate road surface and subgrade at each test section road.

The Finnish Transport Agency (Finra 2005) has designed grading curves to use for estimating E-modulus based on the Odemark bearing capacity design method for roads (Odemark 1949). The comparison has been conducted for each plotted grain size distribution curve. These theoretical E-values calculated from the grain size distribution were defined for each sample. As the DCP, LWFD and FWD measurements were mainly carried out during spring, the design grading curves defined in the Finnish guidelines (Finra 1993) for sample frost susceptibility were taken into account. Reduced estimated E-modulus was used if the grain size distribution of a sample was analogous to the design curves or to the high organic content of a sample. Hereafter, variable Aggregate E_{GSD}, Embankment E_{GSD} and Subgrade E_{GSD} denote the E-modulus estimations based on grain size distributions of the above-mentioned layers.

2.6 Rutting prediction – based on measurement results of studies I–III

In this thesis, bearing capacity values has been measured using three different devices for different study purposes. To determine rutting threshold values in study II, test sections were selected from the test sections of study I. For study III, new test sections were established to study the fly ash structures. A rutting sensitivity table was formulated to assess the rutting risk based on threshold values, and the table is a tentative suggestion for springtime forest road use (Table 9). The table can be tested to assess the rutting risk level based on measured test roads of studies I and III. When the measured bearing capacity value is lower than the specified threshold value, considerable rutting will occur. The table provides an objective framework for determining what happen to a particular road used for timber haulage under specific conditions. However, it is good to remember that the rutting sensitivity table is a tentative proposal for defining rutting risk. Mean values of the bearing capacity measurements represent all the test sections in the study area at a particular measuring round in study I. In study III, the measurement results represent test sections where various fly ash structures were built. The use of the sensitivity table was limited to assessing the situation only under the wheel path. The aim was to assure accurate categorization of rutting likelihood, so as to detect the risk of severe rutting.

2.7 Test structure types and volumes of construction materials for road rehabilitation in studies III–IV

The fly ash material was utilized in four different test structures, which were compared to non-fly ash structures. A total 1936 tonnes of fly ash was utilized to rehabilitate 2400 metres of forest roads. Two test sections of each type were constructed. The initial road structure was left unaltered under the test structures. Other repair phases e.g. improving the drainage of the old road may also have to be performed in certain cases, but these operations were excluded from this thesis. The main interest was to study the technical and economic aspects of fly ash structures. The structures compared in studies III and IV differed slightly from each other. In study III, the non-fly ash structure contained a 100-mm thick aggregate layer with grain sizes between 0 and 32 mm. Adding aggregate is a common rehabilitation method for forest roads. Another reason for this decision was that the fly ash test structures were paved with an aggregate layer of the same thickness as the reference structure. Choosing the same thickness provides the opportunity to investigate the effects of the aggregate on bearing capacity development after rehabilitation. It is denoted hereafter as a reference structure (Ref.) The non-fly ash structure in study IV was a 200-mm thick aggregate layer. It is denoted hereafter as a regular structure (Reg.). A thicker aggregate layer was a consequence of the following reasoning: the test road sections had an approximately 50-MPa bearing capacity value under the wheel path when measured using LFWD. The Finnish Transport Agency has set the target value for gravel roads at 80 MPa to prevent rutting (Finra 2004). The aim of adding an aggregate layer was to reach the above-mentioned target value, which was based on Finnish guidelines for forest roads (Metsätieohjeisto 2001). The thickness of the additional aggregate level is possible to define when the initial stiffness of a road is known. In this case, a 200-mm aggregate layer was be added on top of the initial road to reach the target value.

Figure 8. The road grader formed side barriers and mixed the fly ash and aggregate together on the test sections.

The rehabilitation with fly ash test structures is summarized in the following text. The first (#1) and second (#2) test structures included both aggregate and fly ash mixed together using a road grader, which also strengthened the road sides supporting the test structures (Fig. 8). For a small-scale field experiment such as study III, it was easier to mix the materials at the construction site. In study IV, a central mixer at the quarry was used prior to delivery, which was more suitable for large quantities. In test structure #1, a 50-mm fly ash layer and a 100-mm aggregate layer were mixed. In test structure #2 the thickness of the fly ash and aggregate layers were100 mm and 100 mm respectively, before being mixed together. The motivation for using these combinations was to test the joint effect of fly ash and aggregate on road stiffness. The other two test structures included a uniform fly ash structure with no aggregate mixing. The third (#3) and fourth (#4) test structures had a 250-mm and a 500-mm thick fly ash layer, respectively. Fly ash utilization on the forest roads required an environmental permission, which mandated that a 100-mm thick aggregate layer had to be spread over all the test structures. The thickness of the uniform structures decreased afterwards, due to the compaction caused by an excavator. The excavator was also used to shape the road shoulders of the test sections, providing horizontal support for the test structures (Fig. 9). The fly ash test structures, reference and regular structure profiles are presented in Figure 10.

Figure 9. The excavator shaped the road shoulders to support the test structures.

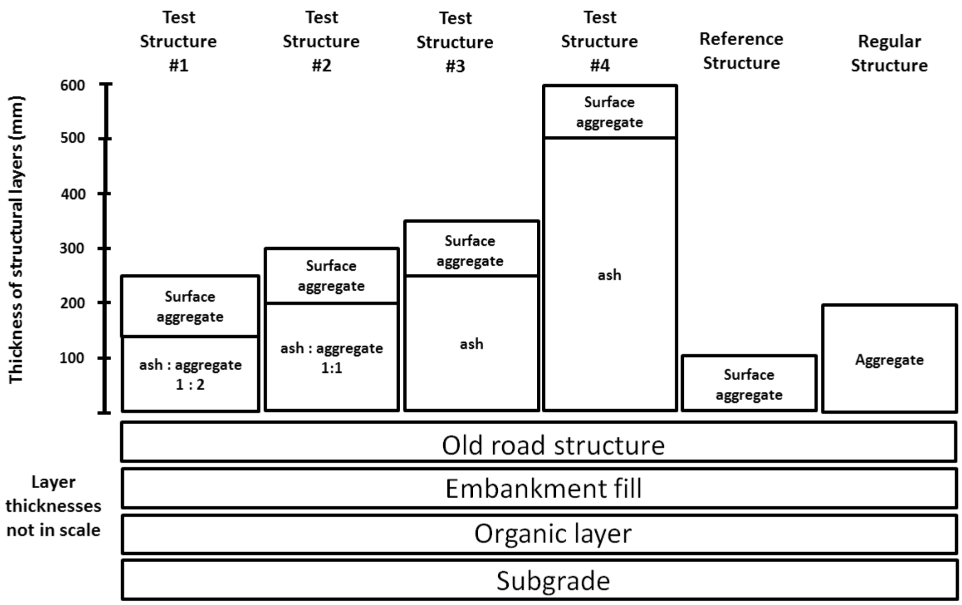


Figure 10. Fly ash test structure profiles #1–#4 for studies III and IV, reference structure for study III and regular structure for study IV.

Based on the experience gained from the fieldwork in study III, the construction procedure was rearranged to provide customized working methods for study IV. The introduction of the implementation differed, therefore between study IV and III. Loose cubic metres of construction materials were used for calculating test structure volumes. Material densities were 1100 kg/m^3 for the fly ash and 1540 kg/m^3 for the aggregate during transportation and construction work. The final thickness of the fly ash test structures was calculated with a 66% compaction rate based on the literature (Tuhkarakentamisen käsikirja 2012). For each test structure, the material volumes of fly ash and aggregate are presented in Table 1. Quantities are presented per kilometre with a road width of 3.6 metres. The quantities given in Table 1 are based on Table 2, which presents construction layer volumes and thicknesses for the test structures.

Table 1. Fly ash (FA) and aggregate (Agg.) quantities (tonnes/km) used for regular and test structure types (rounded-off values in parentheses).

	FA	Agg. for mixing	Surface Agg.	Total
#1	198 (200)	554	554	1307 (1300)
#2	396 (400)	554	554	1505 (1500)
#3	990 (1000)	-	554	1544 (1500)
#4	1980 (2000)	-	554	2534 (2500)
Reg.	-	-	1109	1108 (1100)

Table 2. Fly ash (FA) and aggregate (Agg.) layer thicknesses (m) and volumes (m^3/km) for the regular and test structure types.

	FA, m	Mixed Aggregate, m	Surface Aggregate, m	FA, m^3/km	Aggregate, m^3/km	Total, m^3/km
#1	0.05	0.1	0.1	180	720	900
#2	0.1	0.1	0.1	360	720	1080
#3	0.25	-	0.1	900	360	1260
#4	0.5	-	0.1	1800	360	2160
Reg.	-	-	0.2	-	720	720

2.8 Cost calculation materials in study IV

2.8.1 Definition of work phases and machinery productivity

Several work phases were specified and hourly productivities for the applicable machines were either calculated from the field study or sourced from the South African forest road handbook (2005). The definitions are presented in Table 3. The motivation for phase definition was to enable construction techniques using available machinery. The following machines were chosen: wheeled front-end loader, central mixer, excavator, motor grader and vibration roller. The bucket size of the wheel loader was 3 m^3, and it was used for loading the fly ash and aggregate. The South African forest road handbook (2005) presented various productivity rates for loading per hour: fly ash was estimated to be a very easy material for loading (216 m^3/h) and aggregate was estimated as fairly easy (144 m^3/h) in study IV. The productivity of the central mixer (200 m^3/h) was not used directly for the calculations and it is expressed in parenthesis in Table 3. The productivity of the central mixer was used to estimate that four tip trucks with a gross weight of 76 tonnes were needed to deliver the mixed material directly for utilization. This calculation only included the developer/entrepreneur's price per tonne, because of the varying market prices for mixers, and focus on actual cost calculations. Test structures #3 and #4 were built by the excavator and grader, whose productivity data were collected during the field study. Information provided by the manufacturers was used for the vibration roller and motor grader. They recommended an approximately 19-tonne grader and 8-tonne single drum vibration roller for grading and compaction.

Table 3. The defined work phases and machines selected for the rehabilitation work for both test and regular structures, together with productivities per hour. Column 'Place' specifies work phase location, i.e. whether the work occurred on-site or outside of a rehabilitated forest road. Blank boxes for the tip truck indicate that specifying the per-hour productivity was not possible. Sources: [1] field studies in this thesis; [2] South African forest road handbook and [3] manufacturer.

	Work phase	Place	Machine	Productivity	Unit	Source
Test structures #1 and #2						
1	FA loading	outside	Wheel loader	216	m^3/h	2
2	FA transport	outside	Tip truck			
3	Mixing	outside	Central mixer	(200)	m^3/h	3
4	Mix transport	outside	Tip truck			
5	Grading	on-site	Motor grader	3.750	km/h	3
6	Compact	on-site	Vibration roller	240	m^3/h	3
7	Aggregate Loading	outside	Wheel loader	144	m^3/h	2
8	Aggregate transport	outside	Tip truck			
9	Final Grading	on-site	Motor grader	3.750	km/h	3
Test structures #3 and #4						
1	Side barriers	on-site	Motor grader	0.250	km/h	1
2	FA Loading	outside	Wheel loader	216	m^3/h	2
3	FA transport	outside	Tip truck			
4	Spreading FA	on-site	Excavator	0.083	km/h	1
5	Grading FA	on-site	Excavator	0.250	km/h	1
6	Grading slopes	on-site	Excavator	0.250	km/h	1
7	Compact FA	on-site	Vibration roller	240	m^3/h	3
8	Aggregate Loading	outside	Wheel loader	144	m^3/h	2
9	Aggregate transport	outside	Tip truck			
10	Final grading	on-site	Motor grader	3.750	km/h	3
Regular structure						
1	Aggregate Loading	outside	Wheel loader	144	m^3/h	2
2	Aggregate transport	outside	Tip truck			
3	Final grading	on site	Motor grader	3.750	km/h	3

2.8.2 Cost factors, cost calculation models and construction cost formulas

Machinery

Study IV concentrated especially on the work phase costs for the forest road, which were related to the fly ash test structures. Cost calculation of the machinery was classified into three main categories: (i) fixed costs, (ii) operational costs and (iii) labour costs. The operational and labour costs are called variable costs. The machine sale department and the entrepreneurs involved in the field study provided information concerning the machine cost factors. Table 4 presents the cost factors for excavator, motor grader, vibration roller and wheel loader. Working hour is the unit used for machine cost calculations. The cost per hour unit is also used in the cost calculation equation, which was utilized for each above-mentioned machine. The equations used for the calculations are presented in Equations 1–6.

Annual interest cost (Eq. 4), depreciation cost (Eq. 5) and other miscellaneous costs were included in the fixed costs of all the machines. The miscellaneous costs covered repair and maintenance, fuel, tyres, transfer and insurance costs. Tyre service life was calculated as a constant of three years for the earthmoving machines. Equation 6 presents the total machinery costs summed up as far as they have been taken into account in the study.

Annual interest cost:

$$AC_{int} = \frac{Int}{100} * \frac{PP+SV}{2} \tag{4}$$

Straight-line annual depreciation:

$$AC_{dep} = \frac{PP-SV}{SL} \tag{5}$$

Total annual machinery costs:

$$AC_{mac\ tot} = AC_{int} + AC_{dep} + AC_{rep} + AC_{fuel} + AC_{tyre} + AC_{transp} + AC_{ins} \tag{6}$$

Annual utilization hours vary with labour and operational costs and were included in the variable costs. Annual labour costs were determined in Equation 7. Social security costs and meal compensation for labour were taken into consideration. Other costs, such as the accounting company, rent and communication devices were included in the overhead costs in Equation 8. The total annual costs of the earthmoving machines are presented in Equation 9 with annual risk and the target for business surplus. Lastly, the aim of the calculation process was to obtain total costs per operating hour. It is expressed by the annual total cost divided by the annual utilization time in Equation 10. The final outcomes of the calculations express costs in euros per hour, taking into account the specified level of profitability.

Annual labour cost with travelling expenses

$$AC_{lab} = WH * WC + \left(WH * WC * \frac{IWC}{100}\right) + \mathrm{AC}_{tr} \tag{7}$$

Overhead costs

$$AC_{overh} = \frac{OHC}{100} * \left(\sum_1^{n_{lab}} AC_{lab} + AC_{mac\ tot}\right) \tag{8}$$

Annual total costs

$$AC_{tot} = \left(1 + \frac{A_{rs}}{100}\right) * \left(AC_{mac\ tot} + \sum_1^{n_{lab}} AC_{lab} + AC_{overh}\right) \tag{9}$$

Total cost per operating hour

$$HC_{tot} = \frac{AC_{tot}}{WH} \tag{10}$$

Table 4. Cost factors for a 22-tonne excavator, 19-tonne grader, 8-tonne vibration roller, and 130-kW wheeled front-end loader. Value-added tax (VAT) is excluded. Prices are based on the situation in Finland in 2015.

Cost factor	Excavator	Grader	Vibration roller	Wheel loader	Unit
Fixed costs					
Purchase price of machine	17 5000	35 0000	67 000	145 000	€
Utilization time	1760	880	880	1760	h/a
Service life in years	5	20	5	5	a
Resale value, remaining share of purchase price	35	10	35	35	%
Demand of own capital	30	30	30	30	%
percentage of interest for own capital	3	3	3	3	%
Percentage of interest for borrowed capital	5	5	5	5	%
Insurances	1800	500	250	350	€/a
Overheads (Fixed + Operational + Labour)	5	5	5	5	%
Provision for risks and surplus target	3	3	3	3	%
Operational costs					
Fuel consumption	12	22	8	11	l/h
Fuel price	0.75	0.75	0.75	0.75	€/l
Transfer costs	7500	-	4000	4000	€
Maintenance costs	2.22	3.6	2.0	2.52	€ /h
Tyre costs, service life 3 years	-	1472	2902	2238	€/a
Labour costs					
Hourly wage	14.2	14.2	14.2	14.2	€/h
Amount of workers	1	1	1	1	per./mach.
Duration of working day	8	8	8	8	h/day
Quantity of working day	220	110	110	220	days/a
Indirect wage costs	65	65	65	65	%
Travel and daily allowance	2000	2000	2000	2000	€/a

Truck transport

Avoiding all excessive material transportation from outside the site is important in road construction work to minimize earthmoving costs. In some cases, soil quality or quantity is insufficient for the planned road structure and earthmoving cannot be avoided. Although the basic principles of machinery and transportation cost calculation are similar, some fundamental differences are noted. Cost factors were either distance- or time-dependent. Table 5 presents cost factors for the tip truck based on this grouping. Distance-dependent costs were fuel consumption, maintenance service and tyre costs. Time-dependent costs depended on the actual time consumption of transportation. In Equation 11, fuel consumption was formulated so that the distance was split equally between driving with a load and driving while empty. Regarding tyre costs, the situation with the tip truck was more complex than for the other machinery. Annual tyre costs (Eq. 12) included varying tyre prices and number of tyres along with the option of tyre re-treading on the tractor and trailer. The two above-mentioned equations along with equations 4–10 were used to calculate the total annual costs of trucking.

Table 5. Cost factors for a tip truck (a five-axle, 8x4 power configuration and a four-axle trailer. The total vehicle mass limit was 76 tonnes).

Cost factor	Value	Unit
Time-dependent costs		
Purchase price of tractor	235000	€
Purchase price of trailer	85000	€
Service life in years, tractor	5	a
Service life in years, trailer	10	a
Utilization time	55000	km/a
Resale value, tractor	35	%
Resale value, trailer	10	%
Demand of own capital	30	%
Percentage of interest for own capital	3	%
Percentage of interest for borrowed capital	5	%
Insurances	4500	€/a
Taxes and safety inspection	2000	€/a
Hourly wage	43325	€/h
Amount of workers	1	person/machine
Indirect wage costs	65	%
Duration of working day	8	h/day
Quantity of working day	220	days/a
Travel and daily allowance	500	€/a
Overheads (=fix & var. C.)	5	%
Provision for risks and target surplus	3	%
Distance-dependent costs		
Fuel consumption, loaded	55	l/100km
Fuel consumption, empty	46	l/100km
Fuel price	0.95	€/l
Maintenance costs	5640	€/a
Number of tyres, tractor	14	pcs
Number of tyres, trailer	16	pcs
Tyre service life	80000	km
Tyre price, tractor	809	€/pcs
Tyre price, trailer	467	€/pcs
Re-treading price	250	€/pcs
Number of re-treads during service time	1.5	pcs/tyre

Fuel costs for the tip truck and trailer were calculated using the following equation:

$$AC_{fuel\ tr} = \frac{FCN_{tr\ L}*D_L*PF_{tr}}{100} + \frac{FCN_{tr\ E}*D_E*PF_{tr}}{100} \tag{11}$$

The tyre costs (€ per year) of a tip truck and trailer were calculated using the following equation:

$$AC_{tire} = AD * \left[N_{tr\ tire} * \left(\frac{PR_{tr\ tire}+TRM*PR_{rm\ tire}}{SL_{tire}*(1+TRM)}\right) + N_{tl\ tire} * \left(\frac{PR_{tl\ tire}+TMR*PR_{rm\ tire}}{SL_{tire}*(1+TRM)}\right)\right] \tag{12}$$

Contrary to the calculating costs for the machines per hour, calculation for the tip truck was aimed to gather information about costs per kilometre (Eq. 13). It was therefore necessary to assume that the utilization time of the tip truck is 55 000 km per year. The outcome for cost per transported tonne was formulated in Equation 14, which influenced two significant factors: the transported cargo mass and the driven kilometres.

Costs of the tip truck and trailer per driven kilometre (€/km) were calculated as follows:

$$C_{tr\ km} = \frac{AC_{tot}}{AD} \tag{13}$$

Costs per cargo mass of the tip truck and trailer were calculated using the following equation:

$$C_{tr\ mass} = \frac{C_{tr\ km}*D_{sid}}{M_{tr}} \tag{14}$$

2.8.3 Other cost factors

For test structures #1 and #2, the fly ash and aggregate were mixed together in the central mixer. Several machine types were available for mixing the construction materials. The manufacturer/entrepreneur of the central mixer (modified from an asphalt-mixing machine) gave a price of €6 per tonne for the mixing process, including material input and loading of the mixed materials to the tip truck. The mixing process took place at a quarry. The material cost of the aggregate was set at €5 per tonne.

Transportation costs greatly depended on distance and cargo mass. The following values are case-specific, and therefore they are not directly usable for other studies. Actualized driving distances and cargo masses from study III were implemented in the calculations (Fig. 11). A round trip for the tip truck was 50 km for direct transportation of the fly ash and 20 km for transportation of the aggregate. The fly ash in test structures #1 and # 2 was first delivered to the quarry for mixing, when transportation distance was 15 km. The density of the transported material and the maximum load capacity of the tip truck were ruling factors when determining the total cargo mass. The cargo masses of fly ash and aggregate were 39 and 49 tonnes, respectively. The mass of the mixed material was estimated to be 44 tonnes per cargo.

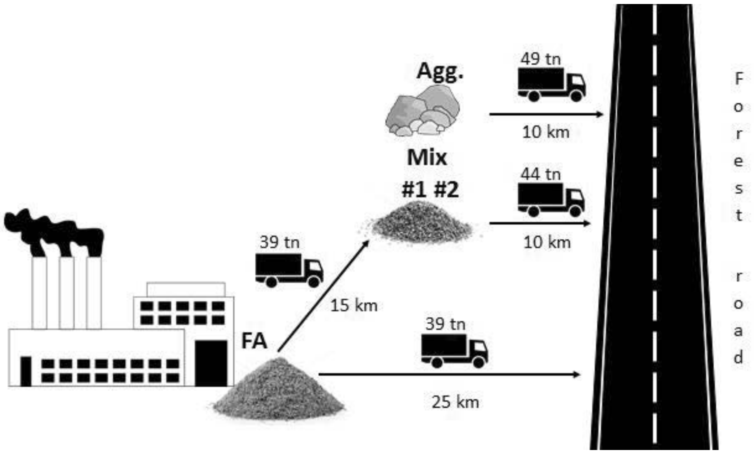


Figure 11. The assumed distances and cargo masses for transport of construction materials.

2.8.4 Total construction cost formulas for test structures

Equations 4–14 were utilized in every relevant addend in Equations 15–17. The material quantities (tonnes/km) of each test structure, the machine productivities of various work phases (km/hour) and the total operational hour costs for each machine (€/hour) were defined for the total construction costs. Exact costs (€/tonne) can be calculated for every work phase by multiplying together these cost factors for each construction work phase in each of the test structures. Multiplying this value with the material quantity of the test structure (tonnes/km) form the final results in euros per kilometre. Total cost formulas for the construction work sorted by construction techniques (15–17), including material costs (€/tonne) and mixing (€/tonne).

Mixed structures (#1 & #2):

$$C_{Total} = C_{FA\ loading} + C_{FA\ transport} + C_{Aggregate} + C_{Mixing} + C_{Mix\ transport} + C_{Grading} + C_{Compact} + C_{Surface\ Aggregate} + C_{Aggregate\ Loading} + C_{Aggregate\ transport} + C_{Final\ grading} \quad (15)$$

Uniform structures (#3 & #4):

$$C_{Total} = C_{Sidebarriers} + C_{FA\ loading} + C_{FA\ transport} + C_{Spreading\ FA} + C_{Grading\ FA} + C_{Grading\ slopes} + C_{Compact\ FA} + C_{Surface\ Aggregate} + C_{Aggregate\ Loading} + C_{Aggregate\ transport} + C_{Final\ grading} \quad (16)$$

Regular structure (20 cm):

$$C_{Total} = C_{Aggregate} + C_{Aggregate\ Loading} + C_{Aggregate\ transport} + C_{Final\ grading} \quad (17)$$

3 RESULTS

3.1 Regression models for E-modulus between measuring devices

Regression models for predicting E_{FWD} on mineral and peat subgrades based on measures from portable tools are presented in Tables 6 and 7. On the peat subgrade (Table 6), including the aggregate layer thickness significantly improved the regression models (model 2 and 4) compared to without the aggregate layer thickness (models 1 and 3). For the mineral subgrade in Table 7, E_{LFWD} or E_{DCP} were the only workable explanatory variables for the regression models, i.e. no significant improvement was observed for the goodness of the models with the addition of the ThicknessAggregate variable. The coefficient of determination of the regression model for E_{LFWD} was higher for the mineral subgrade (r^2 = 0.508) than for the peat subgrade (r^2 = 0.327). The regression model itself was fairly similar in terms of intercepts and slopes, regardless of subgrade type. Instead of peat and mineral soils the regression models were different for predicting E_{FWD} based on E_{DCP}, because peat soil provides a positive y-intercept but in practice mineral soil provides the value 0 on the regression model for E_{FWD} based on E_{DCP}. The regression models to predict E_{LFWD} as a function of the DCP for mineral and peat subgrade are presented in Table 8. A better coefficient of determination was revealed for the regression model of the mineral subgrade compared to peat subgrade soil.

Table 6. Regression model parameters for predicting the Elastic modulus estimated with the Falling Weight Deflectometer (E_{FWD}) from the values from Loadman (E_{LFWD}) and Dynamic Cone Penetrometer (E_{DCP}) for roads built on peat subgrade soils (N=44, SE: standard error).

Model	***1***		***2***		***3***		***4***	
Parameter	***Estimate (SE)***	***Sig.***	***Estimate (SE)***	***Sig.***	***Estimate (SE)***	***Sig.***	***Estimate (SE)***	***Sig.***
Intercept	18.9 (5.5)	.001	41.5 (9.2)	.000	11.9 (9.9)	.236	20.1 (16.3)	.231
E_LFWD	.352 (.077)	.000	.369 (.084)	.000				
E_DCP					.248 (.080)	.003	.397 (.123)	.004
$Thickness_{Agg.}$			-.969 (.266)	.001			-1.12 (.304)	.001
R^2	0.327		0.596		0.183		0.487	

Table 7. Regression models predicting Elastic modulus estimated with the FWD (E_{FWD}) from values from the Loadman (E_{LFWD}) and DCP (E_{DCP}) for roads built on mineral subgrade soils (N=35, SE: standard error).

Model	*1*		*2*	
Parameter	***Estimate (SE)***	***Sig.***	***Estimate (SE)***	***Sig.***
Intercept	19.5 (4.8)	.000	-0.7 (8.5)	.931
E_LFWD	.432 (.073)	.000		
E_DCP			.443 (.082)	.000
R^2	0.508		0.596	

Table 8. Regression models predicting Elastic modulus estimated with the Loadman (E_{LFWD}) based on values from DCP measurements (E_{DCP}) for roads built on peat and mineral subgrade soils (N=35, SE: standard error).

Model	**Peat**		**Mineral**	
Parameter	***Estimate (SE)***	***Sig.***	***Estimate (SE)***	***Sig.***
Intercept	-10.8 (13.2)	.417	-30.6 (13.8)	.033
E_DCP	.629 (.107)	.000	.878 (.131)	.000
R^2	0.444		0.575	

3.2 Rutting prediction

Based on consistent bearing capacity values measured with LFWD, DCP and FWD, it was possible to define threshold values for the E-modulus that indicate the risk of rutting and the severity of a rutting consequence for heavy vehicles on a forest road. Table 9 presents a rutting sensitivity classification for forest roads during the spring thaw, which is based on the bearing capacity measurements of three devices and rutting depth likelihood for heavy truck passes. This table enables the estimation of trafficability so as to decrease the risk of road damages caused by timber haulage. The lower limit of the probability classes for low rutting risk was set as the defined threshold values. To reduce estimation uncertainty it is relevant to also consider the weather forecast for the following days and to visually assess the thawing process on the forest road and ditches before granting permission to begin transportation.

Table 9. A preliminary framework for estimating the risk of rapid rutting during heavy truck passes based on FWD, LFWD and DCP measurements during the spring thaw. The measurement unit is MPa and the measurement point is located on the wheel path.

Likelihood and depth of rutting	E_{FWD}	E_{LFWD}	E_{DCP}
Very high	< 30	< 35	< 70
High	30–35	35–45	70–80
Medium	35–45	45–55	80–115
Small	45–70	55–70	115–150
Very small	> 70	> 70	> 150

3.3 Bearing capacity measurements

3.3.1 Study I

The bearing capacity measurements for assessing the measurement devices were carried out using the LFWD (E_{LFWD}), DCP (E_{DCP}) and FWD (E_{FWD}) devices. The stiffness measurements are presented in Tables 10 and 11, including a classification of the measurement point location (WP or CL) and the number of the measurement rounds for the test road sections on both mineral and peat subgrades. E_{LFWD} values did not vary remarkably between the mineral and peat subgrades at either measurement location. In contrast, E_{LFWD} values of both the centre line and the wheel path were slightly weaker on the mineral subgrade than the peat subgrade. The E_{LFWD} values from the wheel path were generally approximately twice as high as those measured from the centre line for both subgrade types. The E_{DCP} values were ca. 45 percent higher on the wheel path than on the centre line for both the peat and mineral subgrades. The relative variation in E_{DCP} values were less than for the E_{LFWD} values between years, which was also a significant research result.

Table 10. Means and standard deviations (s.d.) of stiffness measurements (MPa) at each measurement point using Light Falling weight Deflectometer (E_{LFWD}), Dynamic Cone Penetrometer (E_{DCP}) and Falling Weight Deflectometer (E_{FWD}). The results are shown for both measurement points (WP: wheel path, CL: centre line).The measurements were conducted on test road over a mineral subgrade.

Mineral	**WP**						**CL**					
	E_{LFWD}		**E_{DCP}**		**E_{FWD}**		**E_{LFWD}**		**E_{DCP}**		**E_{FWD}**	
	Mean (s.d.)	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**
Spring 2009	97 (28)	32	132 (27)	28	56 (22)	8	45 (12)	23	86 (27)	21		
Spring 2010	63 (23)	38	106 (28)	30			35 (10)	27	81 (15)	21		
Spring 2011	66 (25)	42	124 (45)	42			35 (11)	30	76 (15)	30		
Spring 2012	54 (21)	41	101 (24)	42	49 (16)	19	32 (12)	30	79 (20)	30	28 (9)	10
Average	**70 (24)**		**116 (31)**		**53 (19)**		**37 (11)**		**81 (19)**	**26**	**28 (9)**	
Summer 2009	113 (31)	28	159 (50)	28			57 (22)	21	94 (33)	21		

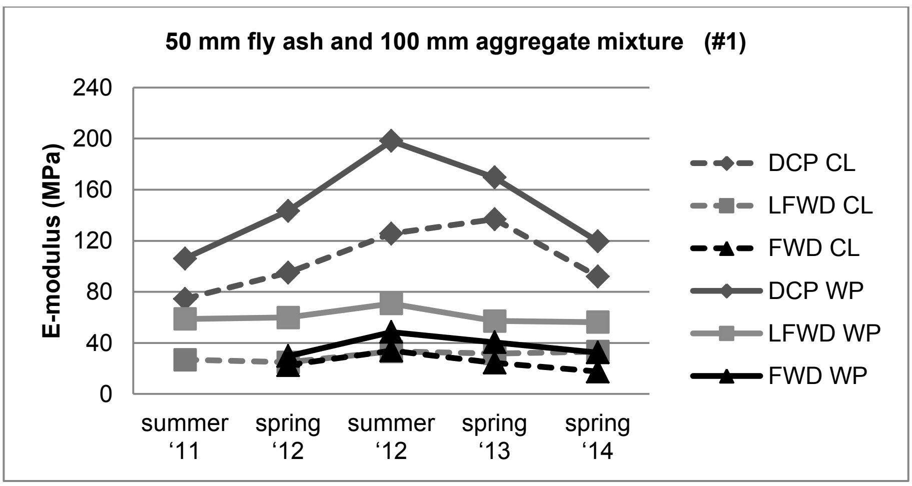
Table 11. Means (and standard deviations) of stiffness measurements (MPa) at all measurement points using the Light Falling Weight Deflectometer (E_{LFWD}), Dynamic Cone Penetrometer (E_{DCP}) and Falling Weight Deflectometer (E_{FWD}). The results are divided by the point of measurement (WP: wheel path, CL: centre line). The measurements were conducted on test road over a peat subgrade.

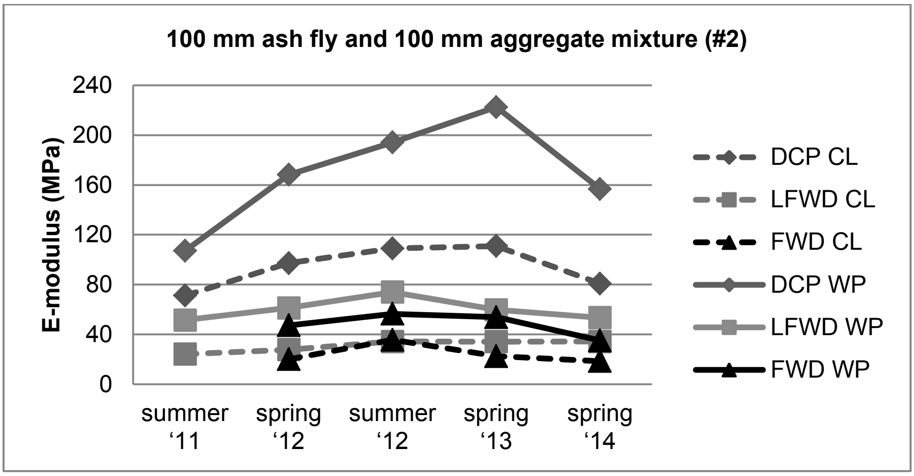
Peat	**WP**						**CL**					
	E_{LFWD}		**E_{DCP}**		**E_{FWD}**		**E_{LFWD}**		**E_{DCP}**		**E_{FWD}**	
	Mean (s.d.)	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**	**Mean (s.d.)**	**N**
Spring 2009	103 (24)	36	144 (19)	34	47 (25)	10	49 (17)	26	94 (36)	27		
Spring 2010	63 (18)	52	122 (28)	45			43 (21)	39	92 (21)	36		
Spring 2011	85 (21)	44	146 (43)	36			40 (14)	33	95 (33)	27		
Spring 2012	65 (25)	48	127 (34)	48	46 (19)	24	34 (14)	36	91 (28)	35	29 (11)	12
Average	**79 (22)**		**135 (31)**		**47 (22)**		**42 (17)**		**93 (30)**		**29 (11)**	
Summer 2009	113 (24)	36	173 (38)	36			55 (23)	27	109 (40)	27		

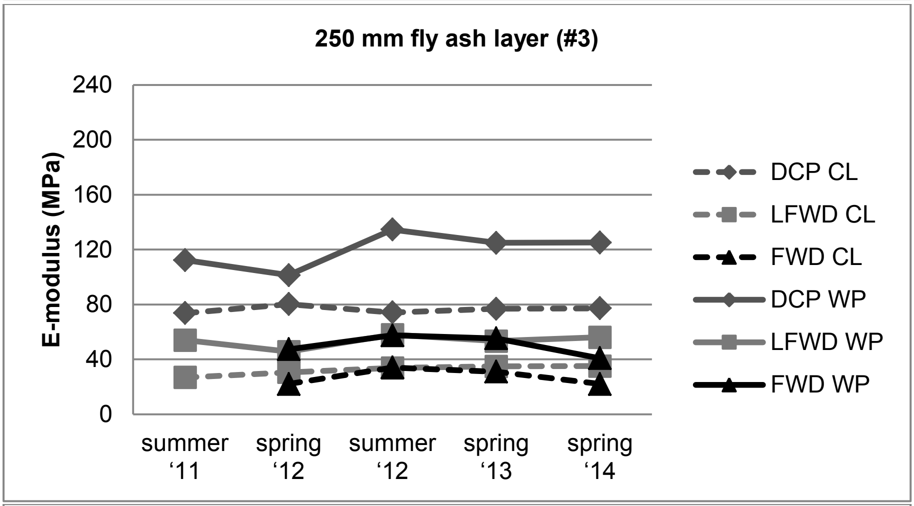
3.3.2 Study III

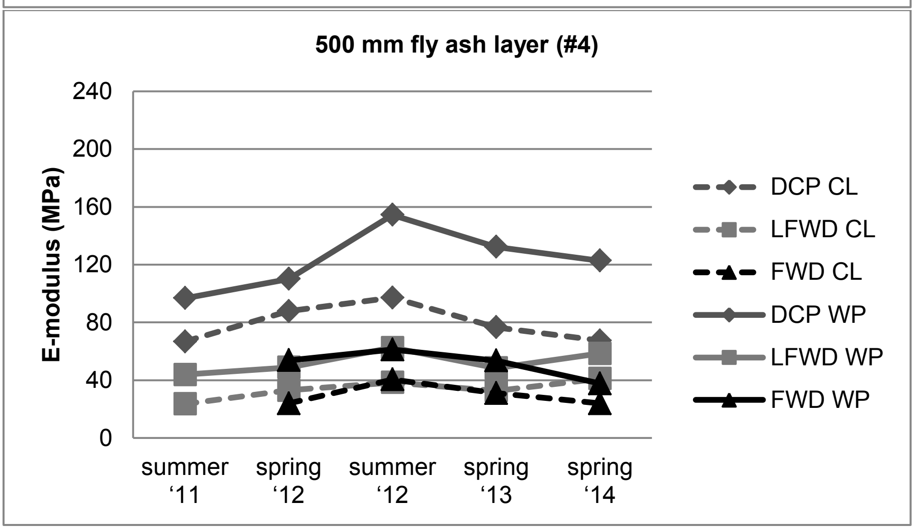
The bearing capacities of the fly ash test structures are presented in Figure 12 in terms of mean MPa. Measurements were collected from two test sections at each test structure. The measurement values were commonly lower for the centre line compared to those measured from the wheel path with all three devices. The values for summer 2011 present the initial situation before rehabilitation in autumn. The measurement round for summer 2012 confirmed a higher bearing capacity for all test structure types than for spring thaw period.

Bearing capacity showed an initial increase, with a slight reduction thereafter. The positive development ended two years after rehabilitation. For each test structure type, the DCP produced the highest measured E-modulus values. Test structure #3 had the poorest bearing capacity (135 MPa), and #4 was only slightly better (154 MPa) at E-modulus values for the DCP. The highest value (222 MPa) was reached on test structure #2 and the second highest on test structure #1 (198 MPa). Improvements on test structure #4 were more noteworthy, because the initial bearing capacity levels were 10–20 MPa lower than for the others. The fourth measurement round indicated a weakened bearing capacity compared to earlier measurement rounds. The bearing capacity still remained at a higher level than for the initial measurements. Surface aggregate did not increase the bearing capacity of the reference structure by very much when measured by the DCP. The E-modulus values of the LFWD did not improve at all. The clearest improvement was observed on test structures #1 and #2, as their highest bearing capacity values were over 70 MPa. Test structures #1, #2 and #3 were at approximately the same level (53–56 MPa) during the last measurement round. Test structure #4 surprisingly had the highest value (59 MPa) during the last measurement round, despite the lowest initial bearing capacity being detected on it. During the entire survey, the lowest bearing capacity was measured on the reference structure. The first E-modulus values for the FWD were measured after rehabilitation. The highest values was measured for #4 (54 MPa) and the next highest for test structures #2 and #3 (47 MPa). The bearing capacities of #1 and the reference structures remained at the lowest level (30 MPa). In the last measurement round, the bearing capacity values were slightly lower than during the first round. Test structures #3 (41 MPa) and #4 (38 MPa) were the best and second best, respectively.




100 mm ash fly and 100 mm aggregate mixture (#2)
E-modulus (MPa)
240
200
160
120
80
40
0
summer '11
spring '12
summer '12
spring '13
spring '14
DCP CL
LFWD CL
FWD CL
DCP WP
LFWD WP
FWD WP


250 mm fly ash layer (#3)
E-modulus (MPa)
240
200
160
120
80
40
0
summer '11
spring '12
summer '12
spring '13
spring '14
DCP CL
LFWD CL
FWD CL
DCP WP
LFWD WP
FWD WP


500 mm fly ash layer (#4)
E-modulus (MPa)
240
200
160
120
80
40
0
summer '11
spring '12
summer '12
spring '13
spring '14
DCP CL
LFWD CL
FWD CL
DCP WP
LFWD WP
FWD WP

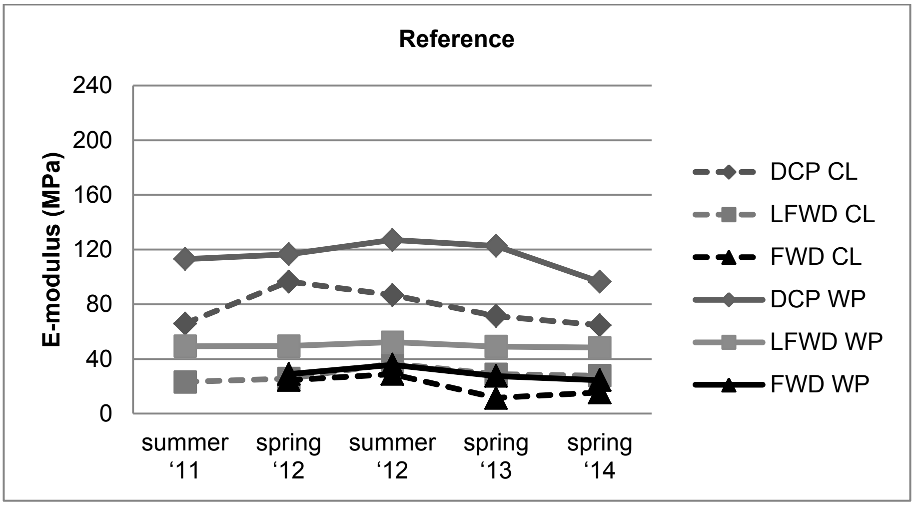


Figure 12. Bearing capacity measurement results for fly ash test structures are presented in the following order: #1, #2, #3, #4 and reference. The measurements were performed with a dynamic cone penetrometer (DCP), a light falling weight deflectometer (LFWD) and a falling weight deflectometer (FWD). CL stands for centre line and WP for wheel path.

3.4 Comparison between rutting sensitivity table and bearing capacity measurements of studies I and III

Rutting risk likelihood is presented in Table 9, where the threshold values are minimum values on class of small risk. The threshold value is 55 MPa for rutting measured by the LFWD device. For several springs, the mean values remained between 54–66 MPa in both subgrade types in study I. According to this, the risk of rutting was relatively small on several test sections. Nevertheless, rutting still remains possible if a heavy vehicle passes on a road during spring. The threshold value for the DCP was defined at 115 MPa. The measurements showed a small risk of rutting, except for two springs on the mineral subgrade, where the risk of rutting was medium. No springtime measurements indicate a high enough bearing capacity to reduce the risk levels during the summer of 2009. The threshold value of the FWD device was 45 MPa. The presumed rutting risk remained small on the peat subgrade, yet very close to the threshold value on the wheel path. The mean values of the FWD were slightly higher for the mineral subgrade, which meant a lower rutting risk during springtime.

When comparing the measured values of the fly ash test sections and the threshold values, it is notable that the first measuring round was carried out before actual rehabilitation by the DCP and LFWD devices during summer. The DCP values for test structures #1and #2 were ca. 115 MPa (threshold value) on the wheel path prior to rehabilitation. Later measurements indicated clear bearing capacity improvement over the threshold value, and the rutting risk decreased to a very low level. The mean values of the LFWD measurement rounds showed a small risk of rutting before rehabilitation during summer and after rehabilitation also during the springtime for test structures #1 and #2, whereas summer measurement after rehabilitation showed a very small risk. For test structure #1, the FWD measurements pointed to a medium risk on the wheel path after rehabilitation. The situation was slightly better for test structure #2, as rutting would presumably be slight. The above-mentioned rutting risk also decreases at test structures #3 and #4 with all three measurement devices. At the reference test section, the LFWD measurement results remained under the threshold value level during the entire study time. The DCP values improved slightly from the medium to the small risk class due to rehabilitation of the reference structure. The rutting risk based on the FWD measurements indicated a high risk of rutting after rehabilitation.

3.5 Statistical observation of bearing capacity for fly ash test structures in study III

Table 12. Statistical significance of paired sample t-test for bearing capacity (Mpa) between measurement rounds ($p<0.05$). Negative values indicate weakened bearing capacity and positive values indicate recovered bearing capacity. Empty box indicates a non-significant change between values.

	Device	Class	Test structure	Summer 2011	Spring 2012	Summer 2012	Spring 2013	Spring 2014
Mean	DCP	WP	#1	106	37	92	64	
Stand.Dev.					*27*	*78*	*41*	
Mean	DCP	CL	#1	74	21		62	
Stand.Dev.					*18*		*42*	
Mean	DCP	WP	#2	107	61	87	115	50
Stand.Dev.					*37*	*17*	*56*	*30*
Mean	DCP	CL	#2	71		38	40	
Stand.Dev.						*28*	*12*	
Mean	DCP	WP	#3	112	-11		13	
Stand.Dev.					*12*		*15*	
Mean	DCP	WP	#4	97		58	36	
Stand.Dev.						*64*	*28*	
Mean	DCP	CL	Ref.	66	31			
Stand.Dev.					*24*			
Mean	LFWD	WP	#1	59		12		
Stand.Dev.						*7*		
Mean	LFWD	CL	#1	27		7		6
Stand.Dev.						*5*		*4*
Mean	LFWD	WP	#2	52		22		
Stand.Dev.						*15*		
Mean	LFWD	CL	#2	24		10	10	10
Stand.Dev.						*6*	*3*	*5*
Mean	LFWD	WP	#3	54	-9			
Stand.Dev.					*8*			
Mean	LFWD	WP	#4	44		19		15
Stand.Dev.						*14*		*9*
Mean	LFWD	CL	Ref.	23	9	15	9	18
Stand.Dev.					*6*	*7*	*6*	*8*

A paired sample t-test was used to compare the initial bearing capacity result and the results of each measurement round after rehabilitation (Table 12). Mean values were calculated separately for each test structure type and compared to the initial. If a calculated value was positive, it indicated improvement of bearing capacity, while a negative value indicated a reduction in bearing capacity. Blank boxes and missing rows indicate that rehabilitation did not statistically improve the bearing capacity. Positive results were most common in the comparison, and only two negative values were observed on the wheel path for test structure #3 during the first comparison. The greatest improvement in bearing capacity was detected in the comparison between the measurement rounds of the same season. Additionally, the improvement was two times more common in test structures #1 and #2 compared to uniform fly ash structures. Approximately the same numbers of statistically significant observations were made at both measurement location classes and with the DCP and LWFD devices. Bearing capacity improved particularly greatly on the wheel path due to the compaction work of traffic than on the centre line. The improvement was higher when a comparison was made of the E-modulus values in the DCP. The reference structure on the wheel path did not show any improvement either through E_{LFWD} or E_{DCP}.

Table 13. Statistically significant results for an independent samples t-test of mean bearing capacity values (MPa) between test structures and the reference structure (P<0.05). The number of observations was based on eight measurements on the wheel path (WP) and six measurements on the centre line (CL). An empty box indicates a non-significant change between values.

	Device	Class	Measuring round	Reference	Test structure #1	#2	#3	#4
Mean	DCP	WP	Spring	116		168		
Stand.Dev.			2012	*36*		*24*		
Mean	DCP	WP	Summer	127		194		
Stand.Dev.			2012	*32*		*24*		
Mean	DCP	WP	Spring	122	169			
Stand.Dev.			2013	*26*	*40*			
Mean	DCP	CL	Spring	71	136			
Stand.Dev.			2013	*30*	*55*			
Mean	DCP	WP	Spring	122		222		
Stand.Dev.			2013	*26*		*42*		
Mean	DCP	CL	Spring	71		110		
Stand.Dev.			2013	*30*		*14*		
Mean	DCP	WP	Spring	96		156		
Stand.Dev.			2014	*25*		*16*		
Mean	LFWD	WP	Summer	52	70			
Stand.Dev.			2012	*7*	*12*			
Mean	LWFD	WP	Summer	52	73			
Stand.Dev.			2012	*7*	*8*			
Mean	LFWD	CL	Spring	28				41
Stand.Dev.			2014	*8*				*5*

A t-test comparison of independent samples is presented in Table 13, where the comparison has been made between the rehabilitated test structures and the reference structure for the same measurement round. If the statistical difference between the reference structure and test structures was significant, the bearing capacity value and its standard deviation are presented in Table 13. Analyses showed statistically significant differences for the E_{DCP} and E_{LFWD} values, but not with E_{FWD}. Almost all statistically significant differences were concerned with test structures #1 and #2 compared to the reference structure. Differences were mainly detected by the DCP and on the wheel path than by the LFWD or on the centre line. No significant differences were found on the first measurement round prior to rehabilitation.

3.6 Cost estimation results of the construction work for fly ash structures in study IV

Costs per working hour are presented in Figure 13 for all four machines. The grader and excavator had the highest hourly costs, €82.4 and €60.6 respectively. Modest hourly costs were achieved for the wheel loader (€56.8) and the vibration roller (€55.9). Machine purchase prices were the main driving factor for hourly costs. Capital costs for the vibration roller and grader were calculated for the entire year, but the utilization times were dictated as six months per year, which increased the hourly costs. The excavator and wheel loader were assumed to be in use year-round. The calculated costs appear reasonable when compared to general prices for earthmoving services.

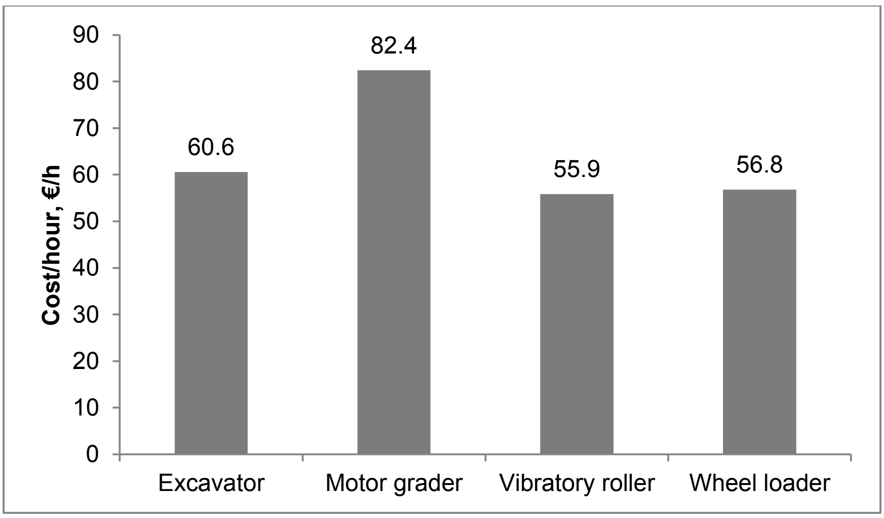


Figure 13. Hourly cost (euro/hr) for earthmoving machines based on above-mentioned Equations 4–10 and cost factors in Tables 1, 2 and 4.

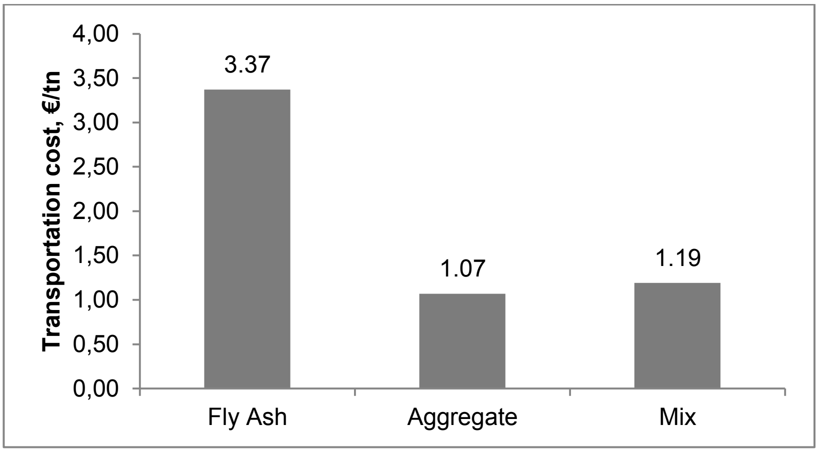


Figure 14. Transportation costs (euro/tonne) for construction materials based on above-mentioned Equations 1–11 and cost factors in Tables 1 and 5.

Figure 14 presents the cost calculation for all construction materials, including transport distances, cargo masses and total quantities. A tip truck with a gross weight of 76 tonnes was used to transport the construction materials. The annual service assumed for the tip truck was 55 000 km, and this same distance was assumed as the annual service time for all transportation schemes, despite differing transportation distances. The outcome of the cost calculations for the fly ash, mixed material and aggregate were 3.37 €/tonne, 1.19 €/tonne and 1.07 €/tonne, respectively.

The final outcome is presented in Table 14, where costs for each test structure are presented in the same order as they are defined in the total cost formulas (Eq. 15–17). As expected, the reference structure was the cheapest alternative, due to its simple structure and the minimal requirement of construction materials. Test structure #3 was the cheapest fly ash structure, and it was only 23% more costly than the regular road. Test structures #1 and #3 were ca. 70% more expensive than the regular road. Test structure #2 was roughly twice as expensive. The aggregate material and the mixing process of the fly ash and aggregate constituted a major share of the costs of test structure #1, 43% and 36% respectively. The above-mentioned work phases were also the most notable for test structure #2, when the share of costs was 38% for the mixing process and 37% for the aggregate material. Greater quantities of fly ash were consumed in test structures #3 and #4, where the transportation of fly ash was correspondingly the most expensive work phase. Other work phases constituted only minor shares of cost for the reconstruction work.

To sum up the cost estimation of the fly ash structures, #3 has the lowest costs. Refraining from utilizing fly ash will also carry an opportunity cost, where the landfill deposition charge is €70 per tonne in Finland. Cost savings would be 60 347 euros per km for test structure #3 based on construction costs and the required fly ash quantity. This cost savings will generally decrease with increasing fly ash transportation distances. The calculation assumed that aggregate is available at a 10-km range from the road under reconstruction.

Table 14. Cost (euro/km) of the forest road reconstruction methods distributed between work phases, when the construction materials include: a mix of fly ash (FA) and aggregate (Agg.) in test structures #1 and #2, a uniform fly ash construction layer in test structures #3 and #4, or a conventional use of aggregate in the regular test structure. The utilized equation numbers are referenced in brackets.

	Test structure				
	#1, [15]	**#2, [15]**	**#3, [16]**	**#4, [16]**	**Regular, [17]**
Side barriers			330	330	
FA loading	52	104	260	520	
FA transport	667	1335	3336	6673	
Aggregate	2772	2772			
Mixing	4514	5702			
Mix transport	895	1131			
Spreading FA			727	727	
Grading mix/FA	22	22	242	242	
Grading shoulders			242	242	
Compact of mix/FA	126	168	209	419	
Surface agg.	2772	2772	2772	2772	5544
Agg. Loading	219	219	219	219	552
Agg. Transport	593	593	593	593	1186
Final grading	22	22	22	22	22
Total	12 654	14 839	8953	12 759	7305

4 DISCUSSION

4.1 Assessment of the measuring devices and their capability to predict rutting on forest roads

Bearing capacity is commonly assessed using a falling weight method to determine soil stiffness. In this thesis, their corresponding E-modulus values were possible to derive from measurement results of each device. The E-modulus of the DCP was based on cone penetration into the soil, whereas the E-moduli of the LFWD and FWD were based on deflection of soil under a falling weight. The indirect E-modulus values of the DCP were calculated using two empirical equations. The FWD and LFWD differed with respect to size and measurement impact scale. The deflection bowl detectors of the FWD were also placed at different distances from the impact point of the falling weight. Hence, the depths of the measurement procedure varied widely. In light of this, it is logical that measurement results for the devices differ for the same measuring point. Such differences were frequently observed in studies I, II and III. On the other hand, device selection can be considered successful where inconsistent measurements provide further research problems to study particular devices in study I. The forest road itself was another motivation for testing the different devices. DCP penetration depth was limited in the wheel path. The non-homogeneous structure of the forest road was also represents uncommon circumstances for utilizing DCP conversion equations. The FWD used a relatively heavy falling weight type of device to detect bearing capacity changes on the forest road. In study

II, the measurement devices were tested for their ability to predict road damages caused by heavy vehicles during the spring thaw. Rut depth measurement was carried out using a precise technique. Bearing capacity data, however, were ambiguous and interpretations are not unquestionable. Underlying factors which also influence forest road trafficability include the thawing process itself and subsequent evaporation. We were able to determine the threshold values of E-modulus for the LFWD, DCP and FWD in study II.

The data collected for assessment of the bearing capacity devices included four springs and one summer period in study I. The data provided a rather satisfactory variation of measured data from different phases of the spring thawing periods. The summer measurements also helped showed the difference between bearing capacities in spring and summer. The data collected also included E-modulus estimations based on grain size distributions of the aggregate layer, embankment fill layer and subgrade layer, in order to enable correlations with the bearing capacity measurements. Study I showed that these relationships were possible to identify along with correlations between the respective measurement values of the devices on the forest road. Study II included limited measurement data concerning rut development during the spring thaw. It contains ten test sections, which were used during the thawing periods of two springs. The rutting sensitivity table represents a tentative proposal but further investigations are needed (Table 9).

Based on the measurement results it is possible to state that subgrade type significantly impacted the bearing capacity values. The observed DCP and LFWD values were higher on the peat subgrade than on the mineral subgrade. The aggregate and embankment fill layers on the peat generally had better material quality with respect to grain size distribution than on the mineral subgrade. The embankment fill layer was also thicker on peat subgrade. These observations were probably the reason for the higher values for bearing capacity on the peat subgrade in study I. Otherwise; the measured bearing capacity was clearly higher under the wheel path than on the centre line, as the wheel path was compacted by traffic. This was immediately obvious in practice, as it was time-consuming to reach the minimum depth for the DCP device in the wheel path. The FWD values correlated with the embankment layer E_{GSD}, which indicated the influence of the embankment fill on the bearing capacity.

Other studies have noted the coefficient of determination between the LFWD and FWD to be 0.513 for asphalt surfaced roads (Pidwerbesky, 1997 b) and 0.245 between the sub-base moduli and the FWD on asphalt-surfaced roads. (Steinert et al. 2005). In study I, the coefficients of determination between the LFWD and FWD were 0.327 on peat subgrades and 0.508 on mineral subgrades. Both portable tools were comparable to the conventional FWD; even if the measuring principles of the LFWD and DCP differ from each other. The DCP provides measures based on the penetration depth of the cone, while the LFWD provides measures based on the upper part of the road. According to Miller et al. 2007, the LFWD can only measure to a depth of approximately 200 mm below the surface. In study I, quite reliable regression models were created for the LFWD, DCP and FWD with a fairly good coefficient of determination. Univariate regression models with E-modulus values of DCP or LFWD could only satisfactorily predict the E-modulus values of the FWD on mineral subgrades. For the peat subgrade, the thickness of the aggregate layer had to be added to the regression models in order to achieve the same R^2 level as for the mineral subgrade. In this case, because the bearing capacity of the peat subgrade was negligible, the upper part of the road structure was a more important determining factor. The same level of determination with this coefficient in the regression model between the portable tools and the FWD model was also gained between the DCP and LFWD. DCP and LFWD are capable of determining bearing capacity, just as the FWD is.

The measurement results of study II clarified the usability of the various devices for assessing the rutting risk classification for forest roads. Interpretation of the rutting results showed clear E-modulus threshold values for each measurement device when rutting measurement was based on mobile laser scanning and the loaded passes of a 34-tonne truck. The estimated threshold values of the E-modulus for the DCP, LFWD and FWD were 115 MPa, 55 MPa and 45 MPa, respectively. Values below these thresholds appear to lead to more than minimal rutting for multiple truck passes within a short time period. The DCP and LFWD were useful for estimating trafficability during the thawing process. The DCP is more suitable for defining thawing depths. Together, the bearing capacity measurements and rutting sensitivity table can be used to avoid rutting or to limit rut development to a defined level on the LVR network during the thawing period. The LFWD and DCP are suitable and convenient for other purposes such as estimating the need for rehabilitation of forest roads and cost-efficient allocation of rehabilitation operations between road sections. LFWD and DCP can also be used for planning of timber harvesting planning to estimate rehabilitation needs prior to timber transportation where road conditions seems poor during visual inspection. The portable tools can also be used to classify forest roads availability, e.g. which roads are passable year-round, which can be used during winter and dry summer and which roads are passable only during the frozen season.

The portable tools are fairly reliable compared to the FWD in evaluating the stiffness of a road structure with certain preconditions. The LFWD performs well when the stiffness of the road surface layer needs measuring. The DCP can determine the thickness of various layers and subgrade types and the stiffness of the structure layers. On the other hand, the DCP requires higher result interpretation expertise from the operator. Contrary to the FWD, both portable tools are flexible and inexpensive to use. The rutting sensitivity table provides a decision-support tool for evaluating forest road condition. Forestry professionals responsible for forest road networks can make decisions concerning trafficability, maintenance and rehabilitation operations more easily based on the LFWD and DCP measurements.

4.2 Comparison of bearing capacity measurements and rutting sensitivity classes

The risk sensitivity table should provide help for crucial times such as spring, when the risk of forest road damages is high. The comparison between the mean values in study I and the threshold values turned out interesting, as no significant deviations were observed between the risk classes measured by the different devices. Therefore, this test run verified the usefulness of the table for rutting risk assessment. Larger differences between the risk sensitivity classes of the devices would reduce the functionality of the threshold values as suitable indicators for predicting road deformation.

After rehabilitation the bearing capacity improvement reduced the rutting risk level, when the test run was executed using the measurement results in study III. The reduction in risk was evidently detected by both the LFWD and DCP measurements. The same observation could not be validated by the FWD, because no measurements were carried out before rehabilitation. The fly ash structures positively impacted the bearing capacity; the rutting sensitivity table showed a decreased rutting risk. The rutting risk typically decreased by one risk level based on the measurements with the portable tools. The above-mentioned observations were detected in all four fly ash structures, but not in the reference structure.

A rutting sensitivity table can assist in assessing the overall situation at times when it is necessary with a general overview during the spring thawing period. The rutting sensitivity table is a promising additional tool for assessing the trafficability of a forest road network and maximizing the benefit gained from bearing capacity measurement devices. However, more data are needed concerning rutting depths and bearing capacity measurements carried out during springtime timber haulage. Extra data would provide more hard facts on the success of the classification.

4.3 Bearing capacities of fly ash test structures

The bearing capacity data from the fly ash test structures were collected during a three-year period, which included two summer season and three spring season measurement rounds. This means that bearing capacity values varied based on rehabilitation success, but also depending on the weather conditions during the measurement rounds, e.g. during spring 2014. Analysing the measurement data by statistical methods confirmed the increased bearing capacity values between the test structures. However, it is good to keep in mind that the statistical analysis does not transform a field test into a laboratory test or reduce the effect of external factors.

The most remarkable observation was that the initial summer bearing capacity level for all the test structure types was reached the next spring after rehabilitation. Improved bearing capacity provided better trafficability during the most crucial time for haulage. The improvements were parallel for every measurement round with the DCP and LFWD. The DCP measurements developed more positively when compared to the LFWD and FWD. DCP may therefore overestimate E-modulus values for these construction materials. Some improvement was detected with the LFWD, but not with the FWD. The poor existing road E_{GSD} values were a consequence of the initial road structure.

Correlations were detected between the E_{DCP} measurement rounds (excluding the fourth round) with the paired sample t-test. Comparisons were made between the initial measurement and three following measurement rounds. Improvement was detected in the summertime E_{LFWD} results compared to the initial values, but not in the springtime measurements. Test structures #1 and #2 had a greater number of statistically significant differences and improvements in bearing capacities were higher than for test structures #3 and #4. The reference did not improve at all during the survey period. However, missing observations create some uncertainty in the functionality of the test structures. The independent sample t-test showed that test structures #1 and #2 evidently had a better bearing capacity than the reference structure during each measurement round based on both the LFWD and DCP results. The independent sample t-test does not show any clear development of the uniform fly ash structures.

Generally, no contradicting results occurred with the bearing capacity measurements, despite results being device-specific. The technical feasibility and reliability of the measurement devices was revealed with similar bearing capacity development trends detected between the test structures and measurement rounds. A greater quantity of fly ash did not improve the bearing capacity; instead improvement appears to be a consequence of adding aggregate. Inadequate compaction during construction work, lack of a better mixing technique and unequal fly ash storage times were probably responsible for this. It appears that the fly ash and aggregate mix performed better than the uniform fly ash layers in this study.

4.4 Cost calculation for fly ash test structures

Cost calculations for the fly ash construction in study IV involved the same test structures as study III. The fly ash quantities utilized in the studies were 200 (#1), 400 (#2), 1000 (#3) and 2000 (#4) tonnes per kilometre. These values help to quantify the fly ash consumption for different road lengths. Work phases were defined separately for uniform fly ash structures and fly ash mixed with aggregate to provide the most suitable outcome. A key principle was the use of widely known machine types, with well-known or measurable productivities. This provides the opportunity for wider utilization of the study results.

The general costs for earthmoving machine work has not been published previously and is not available from entrepreneurs for fly ash construction. Only one direct price for the work phase, provided by an entrepreneur, was used for the mixing process. Two factors in the cost calculations are important to mention to better comprehend the cost calculation results. The profit margin of the entrepreneur was defined as three percent and a machine utilization rate provided by an entrepreneur was used. These have a noteworthy effect on the outcome of our calculations. Equations for the machines have been used previously in other studies, such as Nurminen et al. (2009), and they follow the general principals of cost calculations. It should be kept in mind that the cost factors and source information for the equations may contain shortcomings or inaccuracies in certain parts. The factor with greatest influence on the outcome was the purchase price, service life and annual utilization times. The cost calculation model for trucking involved both time-dependent and distance-dependent costs. The annual utilization time of the tip truck was estimated using a rough adjustment of realistic daily driving speed, which was based on estimated average distance and the number of truckloads per working day. The low fly ash density greatly affected both trucking costs and transportation distance. In conclusion, it is still justified to assume that the calculated work phase costs for reconstruction work on forest roads are applicable. However, the aim was not to present actual machine costs per hour, but instead to compare the costs of various fly ash structures with each other and the regular structure.

Costs deviated between the test structures and likewise the studied structures differ from each other on grounds of the fly ash and aggregate quantities. The total rehabilitation cost for the regular structure was €7305 per kilometre, while rehabilitation by fly ash structures cost 8953–14 839 euros per kilometre. The Finnish Statistical Yearbook of Forestry (2014) presented €12 400 as the average cost of rehabilitation and construction in Finland. Compared to this statistic, the results can be considered very reasonable. Planning and supervision in particular were excluded from the total cost calculation. Also, the total quantity of construction material and the number of work phases were higher than with conventional rehabilitation, where costs are naturally higher. The cheapest fly ash structure was #3, which had a 250-mm thick fly ash layer. This is fairly similar to a situation where an entrepreneur adds an approximately 300-mm thick layer of fly ash on top of an old road before conducting compaction work or adding surface aggregate. The results are considered more reliable when hands-on practice and theoretical methods come to similar conclusion.

Under certain conditions fly ash can be an economically efficient alternative for the rehabilitation of forest roads even though it is more expensive than the regular use of aggregate. Substantial financial benefit can be achieved, when deposition charges are avoided by utilizing fly ash for forest road construction. Cost savings are possible if fly ash is harmless to the environment and suitable from a technical viewpoint. In this situation, test structure #4 provides the greatest cost-savings because of its highest fly ash utilization level. Test structure #3 is the best choice for minimizing the rehabilitation costs of a forest road. Future studies should investigate how to develop more cost-effective construction techniques to bridge the gap between regular structure costs and fly ash structure costs.

REFERENCES

AASTHO (2001). Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT ≤ 400). American Association of State Highway and Transportation Officials, 444 North Capitol st., N.W., Suite 249, Washington, DC 20001. 94 p.

Abdi E., Majnounian B., Darvishsefat A., Mashayekhi Z., Sessions, J. (2009). A GIS-MCE based model for forest road planning. Journal of Forest Science, 55(4): 171–176. https://doi.org/10.17221/52/2008-JFS

Akay A.E. (2003). Minimizing total cost of construction, maintenance, and transportation costs with computer-aided forest road design, Doctoral thesis, Department of Forest Engineering, College of Forestry, Oregon State University 246 p.

Akay A.E., Sessions J. (2005). Applying the decision support system, TRACER, to forest road design. Western Journal of Applied Forestry, 20(3): 184–191. https://doi.org/10.1093/wjaf/20.3.184

ASTM (1993). D 2974-87 Standard test methods for moisture, ash, and organic matter of peat and other organic soils. American Society for Testing and Materials, 1916 Race St., Philadelphia, P.A., 19103. p. 31–33.

Balcom J. (1988). Construction costs for Forest roads. Research Bulletin 64, Forest Research Lab, Oregon State University. 20 p.

Bohrn G., Stampfer, K. (2014). Untreated wood ash as a structural stabilizing material in forest roads. Croatian journal of forest engineering, 35 (1):81–88.

Brito L. (2011). Design Methods for Low Volume Roads. Doctoral thesis, Department of civil engineering, University of Nottingham. 237 p.

Coghlan G. (1999). Opportunities for Low-Volume Roads. Transportation in the Millennium: State of Art and Future Directions, Transportation Research Board, National Research Council, TR News, No. 205. p. 1–7.

Conrad J., Ford W., Groover M., Bolding C., Aust M. (2012). Virginia tech forest road and bladed skid trail cost estimation method. Southern journal of applied forestry, 36(1): 26–32. https://doi.org/10.5849/sjaf.10-023

Cost estimating guide for road construction (2011). USDA Forest Service Northern Region. United States Department of Agriculture. 118 p.

Dai S., Kremer C. (2005). Improvement and validation of Mn/DOT DCP specifications for aggregate base materials and select granular test. Final Report 2005-32. Minnesota Department of Transportation. p. 1–50.

Dwivedi A., Jain M.K. (2014). Fly ash – waste management and overview: A review. Recent Research in Science and Technology 2014, Vol. 6(1): 30–35.

Edil T., Benson H. (2007). Demonstration of ash utilization in low volume roads. Research report 2007-12. Minnesota Department of Transportation. 233 p.

Embacher R.A. (2006). Duration of Spring-Thaw Recovery for Aggregate-Surfaced Roads. Final Report MN/RC-2006-12. Minnesota Department of Transportation, Research Services Section, MS 330, 395 John Ireland Blvd, St. Paul, MN 55155. 289 p. https://doi.org/10.3141/1967-04

Emilsson S. (2006). International handbook: from extraction of forest fuels to ash recycling. Skogstyrelsen, Swedish Forest Agency. 42p.

Finlex (2015). 1401/2015, Laki jäteverolain 5 ja 6 §:n muuttamisesta. [Waste tax Act] http://www.finlex.fi/fi/laki/alkup/2015/20151401 [Cited 12 October 2017].

Finra (1993). Yleiset perusteet, Tierakennustöiden yleiset laatuvaatimukset ja työselitykset. Kehittämiskeskus, Tielaitos, Helsinki. 46 p.

Finra (2005). Tietoa tiensuunnitteluun nro 71D. Tie- ja geotekniikka, Tiehallinto, Helsinki. 13 p.

Ghajar I., Najafi A., Karimimajd A., Boston K., Torabi S. (2013). A program for cost estimation of forest road construction using engineer's method. Forest Science and Technology, 9(3): 111–117. http://dx.doi.org/10.1080/21580103.2012.759163

George K. (2003). Falling Weight Deflectometer for Estimating Subgrade Resilient Moduli." Final Report. Department of Civil Engineering, University of Mississippi. 113 p.

George K., Uddin W. (2000). Subgrade Characterization for Highway Pavement Design. Final Report. Department of Civil Engineering, University of Mississippi. 143 p.

Gerasimov J., Senko S., Karjalainen T. (2013). Prospects of forest road infrastructure development in northwest Russia with proven Nordic solutions. Scandinavian Journal of Forest Research, 28(8): 758–774. https://doi.org/10.1080/02827581.2013.838299

Haywick D. (2004). Pipette and sieve grain size analysis: procedures guide. Third edition. Department of Earth Sciences, University of South Alabama, Alabama. 28 p.

IEA (2017). Coal falls as gas rises: World energy balances in 2016. https://www.iea.org/newsroom/news/2017/august/coal-falls-as-gas-rises-world-energy-balances-in-2016.html [Cited 24 August 2017].

Jukkola S., Melkko M. (1975). Kevytrakenteisten metsäautoteiden rakentaminen. Metsätehonkatsaus 3/1975. 6 p.

Karl H.-D., Lippelt J. (2011). Electricity generation: coal use and cutting CO_2 emissions in the future. CESifo Forum 12(4):68–71.

Kestler M., Berg R., Steinert B., Hanek G., Truebe M., Humprey D. (2007). Determining When to Place and Remove Spring Load Restrictions on Low-Cost Roads. Transportation Research Record: Journal of the Transportation Research Board of the National Academies, Washington, D.C. p. 219–229. http://dx.doi.org/10.3141/1989-67

Kochenderfer J., Wendel G., Smith C. (1984). Cost of and soil loss on “minimum-standard” forest truck roads constructed in the central Appalachians. USDA Forest Service Northeastern Forest Experiment Station, Research paper NE-544. 8 p.

Korpijärvi K., Mroueh U.-M., Merta E., Laine-Ylijoki J., Kivikoski H., Järvelä E., Wahlsröm M., Mäkelä E. (2009). Energiantuotannon tuhkien jalostaminen maarakennuskäyttöön. Processing of fly ash for earth construction. VTT Research notes 2499. VTT Technical Research Centre of Finland. 75 p.

Kottek M., Grieser J., Beck C., Rudolf B., Rubel F. (2006). World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15(3): 259–263. DOI 10.1127/0941-2948/2006/0130

Kumar S., Patil C.B. (2006). Estimation of resource savings due to fly ash utilization in road construction. Resources, Conversation & Recycling 48(2): 125–140. https://doi.org/10.1016/j.resconrec.2006.01.002

Lahtinen P. (2001). Fly ash mixtures as flexible structural materials for low-volume roads. Finnra Reports 70/2001. Finnish Road Administration. 95 p.

Malinen J., Nousiainen V., Palojärvi K., Palander T. (2014). Prospects and Challenges of Timber Trucking in a Changing Operational Environment in Finland. Croatian Journal of Forest Engineering, 35(1): 91–100.

Metla (2014). Metsätilastollinen vuosikirja, Finnish Statistical Yearbook of Forestry. (2014). Finnish Forest Research Institute. 449 p.

Metsätieohjeisto (2001). Metsäteho Oy. 96 p.

Miller H., Kestler M., Amatrudo M., Eaton R., Hall A. (2011). Comparison of test sections of low-volume roadways reconstructed with conventional techniques and full-depth reclamation. Transportation Research Record: Journal of the Transportation Research Board, No. 2204, Transportation Research Board of the National Academies, Washington D.C. p. 206–214. http://dx.doi.org/10.3141/2204-26

Mohammadi S., Nikoudel M., Rahimi H., Khamehchiyan M. (2008). Application of the Dynamic Cone Penetrometer (DCP) for determination of the engineering parameters of sandy soils. Engineering Geology 101: 195–203. https://doi.org/10.1016/j.enggeo.2008.05.006

Moilanen M., Silfverberg K., Hökkä H., Issakainen J. (2005). Wood ash as a fertilizer on drained mires – growth and foliar nutrients of Scots pine. Canadian Journal of Forest Research 35(11): 2734–2742. https://doi.org/10.1139/x05-179

New Zealand Forest Road Engineering Manual (2011). New Zealand Forest Owners Association Incorporated. 150 p.

Odemark N. (1949). Undersökning av elasticitetsegenskaperna hos olika jordarter samt teori för beräkning av beläggingar enligt elasticitetsteorin. Stockholm, Statens väginstitut, Meddelande 77.

Ojala E. (2010). Selvitys puu- ja turvetuhkan lannoite- sekä muusta hyötykäytöstä. Energiateollisuus ry. Finnish Energy Industries. 46 p.

O'Mahony M., Ueberschaer A., Owende P., Ward S. (2000). Bearing capacity of forest access roads built on peat soils. Journal of Terramechanics 37(3): 127–138. https://doi.org/10.1016/S0022-4898(00)00003-3

Paige-Green P., Du Plessis L. (2009). The use and interpretation of the dynamic cone penetrometer (DCP) test. Version 2. CSIR Built Environment. Pretoria, South Africa. 78 p.
Pakkanen E., Leikola M. (2011). Puut perille ja käyttöön, Suomen metsien käytön historia. Metsäkustannus Oy. 512 p.

Patterson S., Acharya S., Thomas J., Bertschi A., Rothwell R. (2004). Integrated soil and crop management, Barley biomass and grain yield and canola seed yield response to land application of wood ash. Agronomy journal 96: 971–977. https://doi.org/10.2134/agronj2004.0971

Pidwerbesky B. (1997 a). Evaluation of non-destructive in-situ tests for unbound granular pavements, IPENZ transactions 24(1): 12–17.

Pidwerbesky B. (1997 b). Predicting rutting in unbound granular basecourses from Loadman and other in-situ non-destructive tests. Road & Transport Research 6(3): 16–25.
Piiparinen H. (2003). Metsäteiden kunnossapitokustannukset Etelä-Suomen yksityismetsissä. Metsätieteen Aikakauskirja 3/2003: 275–290.

Pulkki R. (1982). The Development of an Economical Method for Measuring the Bearing Capacity of Forest Roads. University of Helsinki, Department of Logging and Utilization of Forest products, Research notes No. 42. 85 p.

Pulkki R. (2003). Minimizing negative environmental impacts of forest harvesting operations. Chapter 15. In towards sustainable management of the boreal forest. Edited by Burton P., Messier C., Smith D. Adamowicz W. NCR Research Press, Ottawa, Ontario, Canada. p. 581–608.

Saarenketo T., Aho S. (2005). Managing Spring Thaw Weakening on Low Volume Roads. Roadex II Northern Periphery. 129 p.

Salour F., Erlingsson S. (2013). The influence of groundwater level on the structural behavior of a pavement structure using FWD. Proceedings, Ninth International Conference on the Bearing Capacity of Roads, Railways and Airfields 1: 485–494.

Sessions J., Sessions J. B. (1992). Cost control in forest harvesting and road construction. FAO Forestry paper 99. 106 p.
Siekmeier J., Pinta C., Scott M., Jensen J., Davich P., Camargo F., Beyer M. (2009). Using the Dynamic Cone Penetrometer and Light Weight Deflectometer of Construction Quality Assurance. Minnesota Department of Transportation. Final Report. No. 2009-12. 50 p.

Skogsbilvägar – service, underhåll och upprustning (1991). Forskningsstiftelsen Skogsarbeten, Tryckeri AB Primo, Oskarhamn, Sweden. 71 p.

South African Forest Road Handbook (2005). Forest Engineering Southern Africa. Institute for Commercial Forestry Research. 212 p.

Steinert B., Humphrey D., Kestler M. (2005). Portable Falling Weight Deflectometer Study. Report No. NETCR52. Department of Civil and Environmental Engineering, University of Maine. 277 p.

Supancic K., Obernberger I. (2012). Wood ash utilization as a binder in soil stabilization for road construction – first results of large-scale tests. ASH 2012, Ashes in a Sustainable Society, January 25-27 Stockholm, Sweden. 12 p.

Tasanen T. (2004). Läksi puut ylenemähän Metsien hoidonhistoria Suomessa keskiajalta metsäteollisuuden läpimurtoon 1870-luvulla. The history of silviculture in Finland from Mediaeval to the breakthrough of forest industry in 1870s Metsäntutkimuksen tiedonantoja 920. Metsäntutkimuslaitos 2004. 444 p.

Tuhkarakentamisen käsikirja, Energiantuotannon tuhkat väylä-, kenttä- ja maarakenteissa (2012). [Handbook of Ash Utilisation in Road, Field and Other Soil Structures]. Ramboll Finland Company, Espoo. 65 p.

Uusitalo J. (2010). Introduction to forest operations and technology. JVP Forest Systems Oy. Printed in Kariston Kirjapaino Oy, Hämeenlinna, Finland. 287 p.

Vestin J., Arm M., Nordmark D., Lagerkvist A., Hallgren P., Lind B. (2012). Fly ash as a road construction material. WASCON 2012 Conference proceedings. 8 p.

Von Quintus H.L., Rao C., Minchin R.E., Nazarian S., Maser K.R., Prowell B. (2009). NDT Technology for quality assurance of HMA pavement construction. Transportation research board of the national academies. NCHRP Report 626. Transportation research board, Washington D.C.124 p.

Wang S., Miller A., Llamazos E., Fonseca F., Baxter L. (2008). Biomass fly ash in concrete: Mixture proportioning and mechanical properties. Fuel 87: 365–371. https://doi.org/10.1016/j.fuel.2007.05.026